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An Application of System Dynamics Analysis to Ecosystem Management at the Poinsett Weapons Range, Shaw AFB SC

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PREFACE

This effort demonstrates a systems analysis approach toward addressing long term management strategies using the particular application of management of natural resources. The document is the final capstone course project report of students in the Air Force Institute of Technology's resident masters program in Engineering and Environmental Management. Most participating students are also using this technique in pursuit of their individual thesis research efforts in various technical and management areas and have explored applications of system dynamics modeling at the graduate level.

The attached application addresses specific challenges in ecosystem management related to the operation of the Poinsett Weapons Range maintained by Shaw AFB SC. Issues include long term management of forest systems for control of species composition and biodiversity as well as endangered species management concerns. Findings suggest near term management options which are expected to optimize long term conditions consistent with sustainable Air Force training operations. The report can be used as a reference for fundamental principles in natural resource and endangered species management, as a reference for management of long leaf pine stands and red cockaded woodpecker populations specifically, and, perhaps most importantly, as a reference for how the management tool of system dynamics simulation can be used to address a wide variety of issues surrounding management of complex systems, both natural as well economic and organizational.

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I. Introduction

Problem Statement. One of the more challenging missions for the Environmental Flight at Shaw Air Force Base, North Carolina is the protection of the endangered Red-Cockaded Woodpecker (*Picoides Borealis*) and the management of the Poinsett Weapons Range ecosystem. Currently, the population trends of the Red-Cockaded Woodpecker (RCW) within the Poinsett Weapons Range ecosystem have the potential to negatively impact the base's primary mission of maintaining the highest level of Air Force combat capability and readiness. Short term management efforts to improve the ecosystem are resource intensive. The long-term effects of current management practices on the ecosystem are not clearly understood. A long-term sustainable approach to produce a stable ecosystem with minimum resource expenditure is needed.

Ecosystem Description. The Poinsett Weapons Range is located in Sumter County, South Carolina and is operated by the United States Air Force at Shaw Air Force Base. Resources include 12,500 acres of forested areas which consist of slash pine, longleaf pine, loblolly pine, and various hardwoods (Shaw AFB Natural Resources Management Division, 1996:1). As of February of 1995, the range had nine known active clusters (aggregate of cavity trees used by a RCW group) and eight known inactive clusters (Shaw AFB, 1995). By 1997, the active clusters decreased to six while the inactive clusters rose to ten respectively (Rogers, 1997). The Air Force is obligated to manage the RCW under section 7 of the Endangered Species Act (ESA) and is currently working with the U.S. Fish and Wildlife Service (USFWS) to proactively manage the RCW population in accordance with the ESA requirements. Current habitat management practices include: nesting habitat maintenance, foraging habitat maintenance, burning, erosion control, timber harvesting, pine straw harvesting, restoration and construction of cavities, cluster protection, augmentation/translocation, surveys, and inspections and monitoring.

The RCW is a non-migratory species of woodpecker once common throughout the pine forests of the Southeastern United States, preferring mature longleaf pine savannahs (Jackson, 1994; U.S. Fish and Wildlife Service, 1985:1-88). The RCW population has been significantly reduced due to habitat loss as a result of clearing of the pine forests for agriculture and development. As a result, the RCW has been on the Federal Endangered Species list since 1970. Even though there are six active clusters at the Poinsett Range, only three breeding pairs with one helper per breeding pair and three solitary males currently exist in the Poinsett Range habitat (Rogers, 1997).

The longleaf pine (*Pinus palustris*) is the primary tree used for excavation of cavities by the RCW. The longleaf pine forests were once prevalent throughout the Southeastern United States, stretching from South Carolina to Texas. Since then, fire suppression, livestock, clear cutting, the lumber industry and other human influences, have reduced the range of the longleaf pine significantly. A forest inventory conducted for the Poinsett Range resulted in stands within the 6,098 acres of upland manageable forest being designated as mostly longleaf (42% of stands) and slash pine (39%) (Shaw AFB Natural Resources Management Division, 1996:2).

The health of the ecosystem for this project is primarily determined by the age distribution and density of the longleaf pine stands. Such an LLP ecosystem is hypothesized to be similar to that found in pre-colonial eras and is optimal for RCW sustainability.

Project Purpose. To address the concerns associated with the RCW and its habitat and to explore the implications of various management practices, the project team will employ strategic environmental management and a system dynamics approach to simulate ecosystem processes over a long time period. The purpose of this effort is to gain a better understanding of the ecosystem entities and interrelationships found in a RCW and longleaf pine habitat and to identify the influences driving system behavior and management practices most effective in establishing a long-term stable low-maintenance ecosystem. Improved understanding of these relationships will allow the Shaw AFB Environmental Flight to better manage the range in a sustainable manner.

Client Primary Objectives. The client's primary objectives will influence the entire modeling process. Their objectives (Shelley, 1997) for the project include:

1. Avoiding mission stoppage from regulatory action concerned with RCW issues.

2. Ensuring biodiversity, stability, resilience, etc., consistent with relatively undisturbed ecosystems of the same type in the vicinity.

3. Improving RCW habitat (old longleaf pine) in compliance with the RCW Plan.

4. Achieve sustainable natural resource income to fund the program.

Research Questions. To keep the entire project focused and to ensure the client's objectives are met, specific research questions are addressed. These questions include:

1. How is the number of RCW clusters affected by environmental factors and management practices?
2. What are the impacts on the longleaf pine ecosystem viability if habitat management is driven by RCW population goals?
3. What management practices will be required to restore and to maintain a longleaf pine ecosystem?
4. How much human resource expenditure with regard to management practices is required to maintain a stable ecosystem?
5. What are the effects of management practices on the indicator species? Specifically, RCWs, turkey oaks, and numbers/age structure of longleaf pines?

II. Literature Review

Longleaf Pines

Background. In Pre-Colonial times, the longleaf pine habitat stretched from Texas to South Carolina, encompassing approximately 30 to 60 million acres (Wahlenberg, 1946:8). Today, the longleaf pine habitat occupies less than 5 million acres (Engstrom and others, 1996:336). There are several reasons for the drastic reduction in longleaf pines: 1) use of these trees for lumber and shipbuilding, 2) turpentine production and naval stores, 3) feral livestock consuming the "grass stage" of the longleaf pine, and 4) suppression of natural fires (Wahlenberg, 1946:15-19; Ware and others, 1996:461-462). The lumber, ship building, and turpentine industries served to reduce the existing mature longleaf pines, feral livestock consumed the new seedlings, inhibiting reforestation, and without fire, the forest ecosystem progressed in its natural succession which created habitats in which longleaf pine were at a disadvantage.

Pine Habitat. Longleaf pine thrives where a heavy summer rainfall occurs, the mean temperature varies from 63^{o} to 73^{o} F, and the soil is sandy and well drained (Wahlenberg, 1946:50). These characteristics are secondary to the effects of fire. Where frequent fires occur, at an interval of one to four years, the longleaf pine grows regardless of the soil type or drainage characteristics. Fires inhibit the growth of most trees, especially those found in successional habitats of the longleaf pine. On dry sites these trees include the blackjack oak, (*Quercus marilandica*), bluejack oak (*Q. cinerea*), and dwarf oak (*Q. stelata margaretta*), while on sandy sites the turkey oak (*Q. laevis*) is found. On moist sites, the slash pine (*Liquidambar styraciflua*), southern red oak (*Q. falcata*), and loblolly pine are common. The longleaf pine is a subclimax tree to these species, and without fire, natural succession takes place.

Fire Effects. Longleaf pines have adapted to fire in several ways. When released from the parent the seeds are dormant, and may remain viable in the soil for decades. The seedcoat on the longleaf pine seed inhibits the entrance of water and is only broken by some extreme external influence capable of breaking the seedcoat, such as a fire (Pyne and others, 1996:180). Thus, after a fire, a large number of longleaf pine seedlings will sprout. Another adaptation by longleaf pines to fire is the "grass stage" where the seedling ceases to grow upward, forcing all its growth into the root system (Harlow and others, 1996:139). In the "grass stage" the needles are densely packed, bearing a similar resemblance to a tuft of grass. These needles are high in moisture content which protect the plant from fire. The initial root growth in the "grass stage" also allows the longleaf pine to survive on dry sandy soils and tops of hills, where moisture is less plentiful. On average, the "grass stage" lasts 3 to 7 years in longleaf pine (Harlow and others, 1996:139; Harrar and Harrar, 1962:53). After a low-intensity fire, the energy stored in the root of the tree is used to lift the terminal bud high into the air, protecting it from the next ground fire. During the "grass stage" and subsequent growth period, the longleaf pine suffers the highest mortality, primarily from fire (Harlow and others, 1996:140). This mortality increases in the presence of competition, but the longleaf pine counteracts this competition by being the most fire tolerant southern pine. Also, its needles are considered pyrogenic or fire facilitating, actually increasing the heat of fires in the proximity of the longleaf pine, ensuring other trees will succumb to the effects of fire (Rebertus and others, 1989:60). As the longleaf pine ages, the bark thickens and lower limbs are shed, further reducing fire susceptibility. On mature longleaf pine trees, with a diameter breast height (dbh) of 24-30 inches, the bark varies from 2 to 6 inches in thickness (Sargent, 1965:150).

Growth and Age Distribution. The longleaf pine, after its initial "grass stage", follows a typical growth and maturation cycle similar to other pine trees. Annual growth increases rapidly; at 25 years of age the average longleaf pine is 45 feet tall and 6 inches in dbh and at 70 years of age the average longleaf pine is 70 feet tall and 15 inches in dbh (Harlow and others, 1996:139; Harlow and Harrar, 1958, 90). Annual growth declines markedly after 40 to 50 years with full maturity reached at 150 years (Harlow and others, 1996:1390). Mature longleaf pines reach heights of 80 to 120 feet, with a dbh of 24 to 30 inches; the maximum longleaf pine seen to date is 150 feet in height and 48 inches in dbh (Harrar and Harrar, 1962:51; Sargent, 1965:15; Harlow and Harrar, 1958:84).

The population distribution of the longleaf pine tends to be of an uneven age and the distribution takes on a wave-like appearance, separated by 70 to 100 years. This population distribution has been noted in other long-lived conifers, but may be due to many external influences on their ecosystem, especially man's influence. Experts in silviculture management of longleaf pine ecosystems disagree on application of the uneven aged distribution. Engstrom argues for an uneven age distribution of forests, saying it provides a natural forest structure, composition, and function to sustain native biota (Engstrom and others, 1996:3350). Conner and Rudolph are against uneven aged longleaf pine distributions; they feel it will cause a drastic rise and fall of the RCW population as the longleaf pines available for cavity construction fluctuate (Conner and Rudolph, 1991:71-72).

Reproduction. As part of the reproductive cycle, conifers produce cones full of seeds. Generally, longleaf pines less than 10 years old (< 2 inches dbh) do not produce cones; longleaf pines 10 to 60 years of age (2 to 11.8 inches dbh) are termed subadults and produce few cones; longleaf pines 80 years and older (> 13.7 inches dbh) are termed adults and are the primary cone producers (Platt and others, 1988:500). Once seeds fall, they lie dormant until a fire breaks the external seedcoat. After this occurs, seed germination takes 2 to 5 weeks with a 50 to 75% germination rate (Harlow and Harrar, 1958:90).

Mortality. Mortality in the longleaf pine is caused primarily by fire, beetles, wind, disease, and old age, with fire the major cause of mortality (Conner and others, 1991:533). Some authors state that southern pine beetle infestation is not a normal problem in longleaf pines, but cavity trees have less resistance and may actually attract beetles (Conner and Rudolph, 1995:82,88-89). In cavity trees, mortality also increases due to a higher susceptibility to fire and wind (Conner and others, 1991:532-533). A typical intrinsic mortality rate for the longleaf pine is shown in Table 1. Fire plays an integral part in tree health; once a tree is damaged by fire or lightning, bark beetle infestation and disease often follow (Conner and others, 1991:532).

Table 1. Longleaf Pine Mortality (Fig 5 - Platt and others, 1988:500)

Tree Size (dbh)	Mortality
< 10 cm	4 to 5.0 %
10 to 20 cm	.75 %
20 to 30 cm	.25 %
30 to 40 cm	.5 %
40 to 50 cm	.75 %
50 to 60 cm	1.0 %
60 to 70 cm	1.67 %
70 + cm	3.0%

Turkey Oaks

Background. In the longleaf pine ecosystem, the turkey oaks are found on limited sandy areas (Wahlenberg, 1942:47). At the Poinsett Range, these xeric sandhills are often dry, allowing fire to control the hardwood species, unlike the wetter lowlands where the hardwoods dominate other species. The turkey oaks at the Poinsett Range are the dominant hardwood species among the pines. This is attributed to their resistance to fire which is primarily due to their thick bark and their ability to resprout several shoots from a burned tree. Because of this fire resistance in an area where fire once frequented the area, the turkey oak has the ability to dominate the hardwood populations.

The turkey oaks have an average age of 40 to 50 years and do not usually exceed 40 feet, which would classify them as midstory at the Poinsett Range. The average dbh is 4 inches, and the maximum diameter usually does not exceed 5 to 6 inches at the Poinsett Range. Since the trees are small, especially at the younger ages, McGinty and Christy measured the dbh at 6 inches above ground level rather than the actual breast height (McGinty and Christy, 1976:488). When counting trees, a group of sprouts from one root system counts as one tree, with the age and size of the largest sprout being recorded, even though the root system may be much older. According to McGinty and Christy, a successful species will produce more young than is necessary to survive to maturity. When the young outnumber the old, the age structure is stable (McGinty and Christy, 1976:489). The turkey oak achieves this stability by sending several sprouts up from one root system even though only one tree per root system is recorded.

Fire Effects. According to Rebertus the adult turkey oaks will tolerate mild surface fires while the smaller turkey oaks are more prone to crown fires (Rebertus and others, 1989:66). Although the crown fires kill the smaller trees, the trees will resprout, usually within six months. The fire resistance increases as the trees become larger due to the thicker bark and the higher crown height (Rebertus and others, 1989:66) Since a slower crown death has a tendency to hinder resprout rates, a mild fire may be more effective in controlling the turkey oak populations. Rebertus suggests that the highest probability of killing the trees is found with a dbh between 3.1 and 4.3 inches, while smaller trees have a high resprout rate and larger trees have a high survivability rate (Rebertus and others, 1989:66).

Timber Value. The turkey oak is considered a forest weed along with other such "scrub oaks" (Wahlenberg, 1942:248). The turkey oak has limited value as timber other than the possible exception of firewood. At the Poinsett Range, this is not a viable option due to the strafing mission and the need to protect the RCW habitat. Firewood sales are currently limited to areas along main roads, which limits the economic potential of this practice. The immediate requirement at Poinsett is to remove all hardwood and pine saplings from within 50 feet of active clusters, leaving a basal area of less than 10 feet squared per acre and no hardwoods greater than 1 inch dbh (Shaw AFB, 1995:4). The long-term goal is to reduce the presence of the turkey oak from the entire foraging area of the range through prescribed burning (Shaw AFB, 1995:9). Removal currently consists of employees and volunteers physically cutting the trees, because only hand clearing is permitted within the 200 foot buffer area of the cavities. Even so, prescribed burning will be the method used for the rest of the range unless burning is not feasible or is insufficient to control well advanced hardwood (Shaw AFB, 1995:5). Other options include mechanical removal via rotating blades, hydro axes, and drum choppers. Another solution is the use of herbicides, but this practice is limited by cost, herbicide control, and the undesired affect of killing flora other than the turkey oak. Injecting the herbicide directly into the stump limits these problems while keeping the turkey oak stump from resprouting. However the cost is still a factor and this method is currently not used.

Effect on Wildlife. The turkey oak does have value as the primary source of acorn production, which supports the various fauna at Poinsett. For instance, flying squirrels were found to primarily feed on oak acorns; on average, 74.4% of their annual diet is from oak acorns (Harlow, 1990:189). Their secondary source of food is from pines; on average, 7.68% of their annual diet is from pine seeds and pollen (Harlow, 1990:189). However, the difference in food source is usually attributed to seasonal variations, with acorn consumption occurring in the late fall and winter months and pine seed consumption occurring in the spring and summer months. Reducing the presence of turkey oaks will have a significantly negative impact on the flying squirrels, which is the primary competitor of the RCW for cavities. A reduction in food source will reduce the squirrel population, while a reduction in midstory will reduce their protection and increase predation. To maintain a healthy ecosystem with species other than the RCW, some turkey oaks must remain to provide food and shelter to these species which include deer, turkeys, fox squirrels, and flying squirrels.

Red-Cockaded Woodpecker

Background. The RCW is a federally listed endangered species (since 1970) endemic to the southeastern United States. The RCW was once an abundant resident of the southeastern Piedmont and Coastal Plain, ranging from New Jersey to Texas, and inland to Kentucky, Tennessee, and Missouri (Jackson, 1971:4-29). Most remaining populations are isolated, small, and fragmented, and continue to decline; some populations are stable in their numbers, but none are increasing (Walters, 1991:507).

The RCW inhabits pine habitats, preferring mature longleaf pine savannahs (U.S. Fish and Wildlife Service, 1985:1-88). It is nonmigratory and disperses short distances for a bird its size (Walters and others, 1988:275-305). It is a cooperative breeder, and thus its demography is characterized by the presence of nonbreeding adults, usually males, long generation times and relatively low variance in reproductive output among breeders (Ligon, 1970:255-278; Lennartz and others,1987:77-88; Walters and others, 1988:275-305; Walters, 1991)

Foraging Habitat. RCWs are nonmigratory and territorial throughout the year with territories ranging from 125 to 370 acres in size (DeLotelle and Epting, 1987:258-294;

Hooper and others, 1982:675-682; Porter and Labisky, 1986:239-247; U.S. Fish and Wildlife Service, 1985:1-88; Walters, 1991). The RCW primarily forages on live longleaf pines for arthropods; reports of foraging time spent by RCWs on pines varies from 90 to 95% (Lennartz and Henry, 1985:11; Hooper, 1996:115). The food source of RCWs is made up of different arthropods; almost all of which are found on or in the bark of longleaf pines (Hanula and Franzreb, 1995:488). This includes wood roaches (69.4%), wood borer beetle larvae (5.4%), moth larvae (4.5%), spiders (3.6%), and ant larvae and adults (3.1%).

The RCW obtains its food primarily by scaling bark and pecking. Although both sexes forage on the upper trunk, only females regularly forage low on the trunk, and only males forage regularly on the twigs and limbs (Walters, 1991:507). RCWs prefer pines larger than 5 cm or 2 inches dbh, particularly those greater than 25 cm or 9.8 inches dbh for foraging (Hooper, 1996:115). Foraging area is directly related to pine density (>/= 10 inches dbh) and inversely to hardwoods (>/= 5 inches dbh) (Lennartz and Henry, 1985:11).

Over 60 ranges in the south have been studied for foraging area in relation to RCWs and longleaf pine habitat. On average, 125 acres of pine habitat greater than 30 years in age is required for RCW foraging with approximately 24 pines per acre greater than or equal to 10 inches dbh and less than 43 square feet basal area of hardwood (Lennartz and Henry, 1985:12-16; Hooper, 1996:116). Approximately 40% of the habitat in these studies was greater than 60 years of age and 94% of the foraging area was within .5 miles of the clusters. According to the Shaw AFB RCW Management Plan for Poinsett Weapons Range, their prime foraging habitat is established at 24 pines per acre greater than or equal to 10 inches dbh and 125 acres within .5 miles of the active clusters (Shaw AFB, 1995:5). A population density goal set for RCWs is one clan per 200 to 400 acres of pine and pine-hardwood forest (Lennartz and Henry, 1985:41).

Nesting Habitat. The RCW, unlike other woodpeckers, creates cavity nests in living trees. It prefers longleaf pine forests, usually creating cavities in longleaf pine trees 62 to 156 years of age, 20 to 30 feet above the ground (Ware and others, 1996:477; Conner and others, 1994:728). An average age for cavity trees noted by several authors is 95 years, with age variation from 63 to 176 years (Lennartz and Henry, 1985:5-6; Roise and others, 1990:7). Other authors have noted that as the longleaf pine stand ages, the RCWs continually prefer the older trees (Rudolph and Conner, 1991:459,461-462). The birds usually can only excavate cavities in the older trees, because the cavity chamber must be excavated in the tree's heartwood core and cannot extend into the surrounding sapwood (Walters, 1991:507).

RCW clusters are generally found in trees with densities of 10 to 150 square feet basal area per acre (Lennartz and Henry, 1985:7). Hardwood is usually below 35 square feet basal area per acre and makes up less than 35% of the total stand with average hardwood stocking at 20 square feet basal area per acre and 14% of total tree density (Lennartz and Henry, 1985:8). By law, the cluster pine basal area is required to be 14 to 16 square meters per hectare or 60.9 to 69.6 square feet basal area per acre (Conner and Rudolph, 1995:82).

In a typical cluster, RCWs may form 1 to 30 cavities, depending on the RCW cluster population (Lennartz and Henry, 1985:7). These cavities include actively inhabited cavities, cavities being excavated or enlarged, and inactive or abandoned cavities. Currently, the average number of cavities per cluster for the Poinsett Range RCW population is 5.437 (Rogers, 1997). Trees within a cluster are usually inside a 1500 foot circle, but may be up to 2400 feet apart (Lennartz and Henry, 1985:7). The Shaw AFB RCW Management Plan for Poinsett Weapons Range calls for all pine and hardwood to be removed within 50 feet of all cavity trees (Shaw AFB, 1995:8).

Population Dynamics. RCWs are communal birds, with a breeding male and female usually assisted by several helper birds. There are now six active clusters at the Poinsett Range but only three breeding pairs with one helper per breeding pair (Rogers, 1997). There is no evidence that helpers participate in clutch production (Walters, 1990:508), but they assist in incubation and feeding of nestlings and fledglings (Lennartz and others, 1987; Ligon, 1970:255-278). Many fledglings, nearly all females and many males, disperse from their natal group during their first year to search for a breeding vacancy (Walters, 1991:508). Although many early dispersers are breeders at age one, some are individuals without a territory or mate, and some males are solitary, having a territory but no mate (Walters, 1990:69-101). Three solitary males exist at the Poinsett Range (Rogers, 1997). Individuals that remain on the natal territory and act as helpers usually become breeders by inheriting breeding status through replacement of a deceased individual (Walters, 1991:509).

RCWs compete for breeding vacancies in existing active clusters rather than form new groups. This tactic is adopted by many males, but rarely by females (Walters, 1991:509). Thus, most helpers are natal males that delay dispersal and reproduction. Once males acquire a breeding position they almost always hold it until they die, but breeding females sometimes switch groups (Walters, 1990:69-101; Walters and others, 1988:275-305).

New groups, if formed, are created by occupying abandoned territories or generating new territories. New territories are forged through pioneering in which a new cluster of cavities is constructed in an unoccupied territory or budding in which an existing territory and set of clusters is divided in two separate territories. Reoccupation of abandoned territories seems to be the preferred method for forming new groups with very little actual pioneering or budding observed in general, possibly due to the four to seven year construction time for a cavity. (Walters and others, 1988:301; Walters, 1991:509; Barlow, 1995:729). For example, in a population of over 200 groups in the Sandhills of North Carolina, only six new groups were formed from budding in eight years, and pioneering was not observed (Copeyon and others, 1991:549). If a territory is abandoned for more than two years, it usually remains abandoned (Walters, 1991:509).

Reproduction and Mortality. A group of RCWs produces a single nest within each active cluster. The clutch size is two to four, averaging just over three throughout the species' range (Ligon, 1970:255-278; Lennaratz and others, 1987:77-88). Presently, the fertility rate for breeding pairs in the Poinsett Range territory is one successful nest per year (Rogers, 1997). For particularly small isolated populations of RCW such as the Poinsett Range, inbreeding may affect the overall fertility of the population. Females rarely remain on their natal territories, and, if they do, avoid related males (Walters, 1990:82).

Although the lifespan of an RCW can reach thirteen years, the typical lifespan of an RCW for the Poinsett Range territory is four to five years (Barlow, 1995:729; Rogers, 1997). Increased mortality of the RCW species is linked more to habitat loss and alteration (loss of cavities) than to increased natural mortality or predation rates (Barlow, 1995:729; Walters, 1991:507). Actual mortality rates not only differ for age and gender, but also change depending on the male's status. Table 2 illustrates the various mortality rates for a one year interval.

Table 2. Mortality Rates for the RCW (Walters, 1990:90)

	Status Class				
Age (Years)	Breeding Females	Breeding Males	Helper Males	Solitary Males	All Males
1	.33	.27	.21	.47	.26
2	.27	.16	.23	.29	.21
3	.28	.14	.31	---	.21
4	.30	.14	---	---	.18
5	.17	.20	---	---	.21

Regulation and Management. The USFWS enacted a recovery plan for the RCW in 1985 to increase the species to 15 populations with 400 to 500 family groups per population (Peters, 1996:27). Whether such regulation is viable is controversial with some authors criticizing the USFWS for setting unreachable population targets for most RCW territories (Bonnie, 1997:18-19; Walters, 1991:519-521). Instead of population targets, proper long-term management of the habitat may be necessary to ensure survival of the RCW with some short-term measures taken to address those populations in imminent danger of extirpation. Several management techniques have been proposed to accomplish this task such as controlling the hardwood midstory and understory, thinning pines within RCW cluster areas, utilizing cavity restrictors and artificial cavities, translocating RCW breeders, and reintroducing breeding pairs to abandoned territories (Conner and others, 1995:140). Artificial management techniques such as cavity restrictors are relatively short-term measures while habitat management plans such as controlling hardwood through prescribed burning can be done to secure the long-term success of the RCW (Conner and others, 1995:149).

Cavity Competitors

Research suggests that the cavity nesting density of RCWs is not limited by the number of cavities, but is a function of the total number of cavities in a given area and the percentage of those cavities that are occupied by RCWs. This same research also suggests that cavity competitors prefer RCW cavities over excavating new cavities in snags, and that the main factor affecting occupation of RCW cavities by these cavity competitor species is the abundance of the other species. (Everhart and others, 1993:41-42). Flying squirrels inhabit the same ecosystem as RCWs and are a major competitor for RCW cavities (Harlow, 1990:187). The primary competitor for RCW cavities observed by the Shaw Air Force personnel at the Poinsett Range is the southern flying squirrel.

<u>Flying Squirrel Cavity Preferences</u>. One study concluded the flying squirrel prefers enlarged RCW chambers, but does not show a preference for enlarged cavity openings versus normal cavity openings (Rossell and Gorsira, 1996:23) However, other studies have shown that the southern flying squirrel prefer cavities with smaller entrances, entrance indices (vertical entrance diameter multiplied by horizontal entrance diameter) of less than 50, and that flying squirrels prefer normal sized cavities

over enlarged cavities (Loeb, 1993:331-332). It should be noted in addition to using the measurements at the entrance at the face of the tree, the Loeb study also used the smallest vertical and horizontal diameters in the entry way and only examined cavities for competitor habitation once per year (Loeb, 1993:330). A third study seems to verify the flying squirrels preference for cavity openings with < 3.5 inches and points out that flying squirrels can occupy cavities regardless of the quantity of the resin barrier diameters (Rudolph and others, 1990:30,32).

Flying Squirrel Homes. The home-range for flying squirrels, considering the horizontal landscape (planimetric area) has been observed at 9.4 acres and 19.3 acres for female and male flying squirrels respectively (Stone and others, 1997:106). The Stone study also observed that 54% of the flying squirrel den sites were in nest boxes, and the remaining den sites were in natural cavities contained in snag or living trees. (Stone and others, 1997:110-111). The squirrels typically use three or more different cavities for their primary nest, escape nest and feed station (Sawyer and Rose, 1985:241). The flying squirrel will nest in nesting boxes, so the use of nesting boxes increases the number of available primary nesting sites (Sawyer and Rose, 1985:242). Flying squirrels have been found living in trees up to 46 feet away from the next nearest tree which would suggest clearing the midstory away from cavity trees will not effectively keep flying squirrels from RCW cavities (Loeb, 1993:333). Southern flying squirrels are also able to return to their home range even when displaced up to 3280 feet (Sawyer and Rose, 1985:242)

Flying Squirrel Birth/Death Rates. Although exact birth and mortality rates could not be found, it has be noted that the southern flying squirrel in North Carolina have 2.8

pups in their spring litter. While autumn litters for flying squirrels raised in captivity averaged 4.0 pups per litter, but this may be inflated due to the effects of laboratory rearing (Sawyer and Rose, 1985:242). Since the flying squirrel is a nocturnal animal, owls are the major predator of the flying squirrel. For example, in Western North America, flying squirrels make up at least half of the spotted owl's diet and a pair of owls could consume 500 squirrels per year (Wells-Gosling, 1985:60). Although predation of squirrels by snakes occurs in the southern states (Wells-Gosling, 1985:62), experiments with the black rat snake have shown a low success rate (3 successful climbs per 18 attempts) in climbing trees protected by a resin barrier (Rudolph and others, 1990:19).

Flying Squirrel Foraging Habits. Studies of the food habits of the southern flying squirrels from the coastal plain of South Carolina determined acorns are the major food source for the squirrel year-round with the flying squirrels primarily feeding on oak acorns; on average, 74.4% of their annual diet is from oak acorns (Harlow, 1990:189 - 190). Under ideal conditions it is estimated a squirrel could store 15,000 acorns in one season (Wells-Gosling, 1985:80). Their second primary source of food is from pines; on average, 7.68% of their annual diet is from pine seeds and pollen (Harlow, 1990:189).

Cavity Trees

RCW Cavity Tree Selection. Cavity tree selection by RCWs appears to be a function of tree age as well as spatial characteristics. Studies indicate that RCWs prefer longleaf pines that are an average age of 95 years for cavity initiation (Jackson and others, 1979:102). However, many studies have found RCWs living in younger trees due to the lack of older pines in an area and in these cases, the RCWs prefer younger trees that have heartwood decay (Hooper, 1988:392-397). Conner found that they also prefer younger trees with thinner sapwood and greater heartwood diameter than other trees in the area. The RCW requires approximately 6 inches in diameter of heartwood to excavate a cavity (Conner and others, 1994:732).

Spatial and forest characteristics also influence where RCWs prefer to roost. The RCWs prefer cavity trees that are surrounded by fewer and shorter hardwoods. Although studies have been performed on this behavior, researchers are unsure how the midstory encroachment causes RCW population decline and if hardwood removal will necessarily cause a return of the RCW (Kelly and others, 1993:126-127). Ross found that the RCWs also prefer trees on the edge of tree stands because they are healthier and have higher resin flows than trees on the interior of the stand. Generally, open stands (stands with more edge trees) are kept open by frequent fires which create a mosaic of clearings and healthier pines (Ross and others, 1997:151-152). Spatial characteristics between RCW clusters are also important as noted by Thomlinson (1996:352) who found that RCW clusters that became inactive were isolated from other clusters or their tree stand became too small.

Cavity Tree Mortality. Cavity trees experience a higher mortality rate than typical older pine trees and the major causes of mortality include bark beetles, wind snap, and fire. In eastern Texas, bark beetles accounted for 53% of cavity tree mortality, wind snap 30%, and fire 7%. However, the majority of these cavity trees were loblolly pine. Of the 27 longleaf pine cavity tree deaths in the study, 33% were killed by prescribed fire, 22% by bark beetles, 19% windsnapped, and 15% by old age. Longleaf pine cavity trees are more vulnerable to fire due to the large amount of resin that seeps from resin wells and flows close to the ground (Conner and others, 1991:534-536). This copious production of resin also keeps longleaf pines from being as susceptible to southern pine beetle infestation as compared to other southern pine species (Conner and Rudolph, 1995:82).

Cavity Enlargement. Cavity enlargement by pileated woodpeckers accounts for another major loss of tree cavities. Conner and Rudolph's study in eastern Texas found that 20% of known RCW cavities were enlarged over a seven year period (Conner and others, 1991:535).

Cavity Creation and Protection. Artificial cavity creation and metal restrictor plate installation are the primary management practices for increasing acceptable cavity numbers. Artificial cavities are created through drilling or by installing a cavity insert, which is basically a nesting box installed within the tree (Copeyon and others, 1991:550; Edwards and others 1997:231). The RCWs tend to prefer artificial cavities to existing vacant natural cavities and the creation of artificial cavities has been successful in increasing reoccupancy of abandoned clusters (Copeyon and others, 1991:554). Metal restrictor plates are typically installed to restore enlarged cavity entrance holes (greater than two inch diameter) or where the threat of enlargement is great (Shaw AFB, 1995:5).

III. Methodology

To successively meet the objectives of any environmental management challenge, a specific plan or approach is necessary to ensure the field customer's needs are satisfied in a timely manner. Deciding which approach is appropriate depends on the nature of the problem and the client's objectives in solving the problem. This particular consulting problem concerning the plight of the RCW and its habitat centers on an ecosystem where change naturally occurs over time and the complexity of such change stems from the internal interactions of the system as well as forces external to the system. To understand the implications of various management alternatives on such dynamic interrelationships, systems thinking and ecosystem dynamics modeling prove ideal.

Typically, decisions which involve environmental issues consist of a large number of influences that must be considered because environmental systems are large and complex. People are unable to analyze several variables at a time which often limits the complexity of their decision making (Gordon, 1885:4). Mental maps (causal connections of the influences) seldom incorporate feedback loops, multiple interactions, time delays, and non-linear interactions. Adding dynamic changes over time introduces greater complexity which causes people to perform below potential (Sterman, 1996:103-106). The system dynamics process accounts for feedback loops, multiple interactions, time delays, non-linearity, and changes in the system over time. The structure of the system dynamics process identifies the underlying mechanisms that drive the basic system behavior. Policy maker's knowledge and system information can be coded into the system dynamics model which enable the client to understand both the short-term and long-term consequences of their management alternatives (Morecroft, 1996:191).

For this project, the system dynamics approach allows for the exploration of management alternatives which accomplish the clients overall objectives of maintaining appropriate endangered species population levels and pursuing long-term stability for the Poinsett Range ecosystem without sacrificing Air Force mission capability. Accordingly, the methodology for this capstone project parallels the system dynamics modeling process. It should be noted that the system dynamics process is an iterative one, requiring the team to repeat and modify any one of the modeling stages as necessary to ensure the model becomes a true mechanistic representation of the ecosystem.

Conceptualization

To properly identify the problem to be solved, the team must become familiar with the general problem scenario. The team must also continually interact with the client to ensure the appropriate problem is addressed and to account for all client concerns. (Three face-to-face meetings are planned along with both telephone and e-mail contact as necessary.) It is during this process that the client may identify new research questions, different approaches, various management practices, or even discover that a system dynamics approach may not be appropriate for the questions addressed.

Literature Review. Initially, an extensive literature review will be conducted in order for the team to fully comprehend the entities and relationships driving ecosystem behavior. The primary focus will be to determine what affects the behavior and habitat of the chosen indicator species, the RCW. The literature review includes contacting the client when necessary to answer specific Poinsett Range ecosystem questions and consulting with available experts well-acquainted with the RCW and its habitat. It is important that the literature review continue throughout the model building phase as questions dealing with plausible parameter values, system mechanisms, and system relationships arise. Once a general literature review is completed, a formal problem statement will be derived.

Problem Statement. To delineate the client's objectives and define the question to be addressed, an initial problem and purpose statement must be formulated. The initial problem statement emphasizes the proper scope through which to solve the problem. The purpose statement emphasizes the employment of the system dynamics approach as the appropriate method in addressing the problem and accomplishing client objectives. The client and project team will finalize the initial statements and establish a joint consensus with regard to the appropriateness and scope of the statements. Such consultation precludes any misunderstandings stemming from the verbiage used to formulate the statements or the employment of the system dynamics approach. Finally, minimum requirements for meeting objectives and system indicators used to measure validity of the model will be jointly determined with the client. The finalized problem and purpose statements are used to focus the overall modeling effort.

Reference Mode. A reference mode, or the expected behavior over the time period of interest, is derived by analyzing the problem statement, available historical data of the ecosystem, systems found in the literature, and client input. This reference mode will be finalized by the project team after iterative review with the client.

Influence Diagram. An influence diagram representing cause-and-effect relationships between the important entities which best represent the system will be constructed by the project team. Using data gathered from the literature review, entities essential to the ecosystem will be initially identified. Based upon this data and the reference mode, the influences between these entities will be defined and should generate feedback loops describing the basic mechanisms responsible for behavior of the system. The level of aggregation and system boundary necessary to incorporate all relevant entities and influences are determined by the questions the client wants the project team to answer. Prior to coding the influence diagram into STELLA, a software modeling package from High Performance Systems, the diagram will be presented to the client to ensure that the diagram incorporates the basic mechanisms responsible for ecosystem behavior and mechanistically describes the system's relationships. Due to relevant client input and additional literature review, the influence diagram may be altered accordingly to achieve the most accurate causal diagram.

Formulation

Model Construction. Once the system's mechanisms have been defined, flow diagrams will be created to represent the mechanisms. The system dynamics model is constructed by coding the flow diagrams into the STELLA computer modeling software which utilizes the Euler method of numerical integration. The model will contain three main sectors: RCW, cavities, and trees. Each sector postulates a detailed structure depicting the flow diagrams with appropriate levels and rates selected from gathered data. Equations defining such levels and rates, as well as any parameter values, will be formulated from data and client input. Assumptions regarding any model formulations, parameter values, or relationships will be documented and approved by the client before being employed in the model.

Testing

Testing the Dynamic Hypothesis. Initial model runs will be conducted to determine whether the basic mechanisms of the model reflect the reference mode. If the model does not reflect the reference mode, additional review will be required to determine if it includes all of the essential variables and mechanisms responsible for system behavior, if the assumed relationships are reasonable, and if the parameter values are plausible. Other validity tests which will be employed include: the extreme conditions test which considers plausible maximum and minimum parameter values and their effects on model output; the boundary adequacy test which analyzes behavior with and without model structure; and the behavior anomaly test which traces anomalous behavior back to a structural cause, leading to the identification of unrecognized behavior in the real system.

Sensitivity testing, which identifies the attributes of the model most sensitive to perturbations or manipulations of the model, will be conducted and reviewed with the client. All model results will be compared to client intuition concerning the system. Counterintuitive output will be examined to determine if modification of the model is necessary. After testing is concluded, the model will be modified accordingly, consulting with the client and performing additional literature review to correct any discrepancies. Model structures will be modified until the project team and client are satisfied the model is an accurate representation of the ecosystem under study.

Implementation

Testing Management Decisions/Policies. Specific predetermined management scenarios, as requested by the client, will be applied to the model to test responses to these policies. From the model runs, alternative strategies in managing the Poinsett Range ecosystem will be explored to view the possible short- and long-range consequences of the strategies.

Presentation of Findings. Results from model runs will be consolidated and translated into a useable form for the client to facilitate use of the model output for decision-making purposes. Any counterintuitive results will be presented and explained to ensure the client fully understands all of the phenomena driving ecosystem behavior. Assumptions for the model, although previously discussed with the client, will be reemphasized to ensure the context of the model's scope and structure is well understood. The focus of the presentation will center on offering the client insight into managing their ecosystem effectively while addressing the dilemmas associated with balancing the concerns of the RCW, long-range Poinsett Range ecosystem stability, and Air Force mission capability.

IV. Model Presentation

The system dynamics model structure for the project incorporates three major sectors to represent the Longleaf Pine (LLP) ecosystem: tree, cavity, and Red-Cockaded Woodpecker (RCW) sectors. The tree section, LLP and turkey oaks, is based primarily on age class division and includes tree germination, tree health, tree mortality, and tree mechanical removal. The cavity section focuses on total cavities in the ecosystem and their construction by addressing acceptable and available cavities, RCW occupied cavities, flying squirrel occupied cavities, unacceptable cavities, and both artificial and natural cavity construction. The RCW section utilizes the RCW life span as the basic building block for its structure. From the life span structure, critical entities influencing the RCW population are modeled such as breeding pairs, cluster availability, cavity availability, available helpers, foraging area, and inbreeding aversion. Each sector of the model is structured according to numerous general and detailed assumptions for the entities and their interrelationships. Appendix A lists the general and detailed assumptions made for each sub-model.

Tree Sector Model Structure

The LLP population is divided into four age classes: 1 to 30 years, 30 to 60 years, 60 to 95 years, and 95 years and older. The maturation rate for these age classes is assumed to be one divided by the number of years in age class. For example, in the 1 to 30 year age group, 1/30 of the trees will mature and move to the next higher age class each year. LLP populations are increased only by germination from pine cones. An artificial planting rate can be assumed to be included in this germination rate. The turkey oak population is handled as one age category, i.e. it is not broken into various age classes.

Longleaf Pines (1 to 30 Years). The LLP from 1 to 30 years old have a dbh of 0 to 8 inches with an average dbh of 4 inches. LLPs from 1 to 30 years old have a mortality rate, a mechanical removal rate (thinning/harvesting), and a maturation rate to older pines. The mortality rate consists of natural mortality, percentage of deaths to trees due to burning, Ips beetle infestation, and southern pine beetle infestation. The ideal LLP under 30 years population is assumed to be 150 trees per acre over 8000 acres, or 1,200,000 trees total.

Longleaf Pines (30 to 60 Years). The LLP from 30 to 60 years old have a dbh of 8 to 16 inches with an average dbh of 12 inches. The trees in this age group are of acceptable size to provide for good foraging area, but cavity construction is not yet possible in these trees. LLPs from 30 to 60 years old have a mortality rate, a mechanical removal rate (thinning/harvesting), and a maturation rate to older pines. The mortality rate consists of natural mortality, percentage of deaths to trees due to burning, Ips beetle infestation, and southern pine beetle infestation. The ideal LLP density for the 30 to 60 years population is assumed to be 20 trees per acre over 8000 acres, or 160,000 trees total.

Longleaf Pines (60 to 95 Years). The LLPs from 60 to 95 years old have a dbh of 16 to 20 inches with an average dbh of 18 inches. These trees are also acceptable for foraging. Artificial cavities can be constructed in these trees. LLPs from 60 to 95 years old have a mortality rate, a mechanical removal rate (thinning/harvesting), and a maturation rate to older pines. The mortality rate consists of natural mortality, percentage of deaths to trees due to burning, Ips Beetle infestation, and southern pine beetle infestation. The ideal LLP density for the 60 to 95 years population is assumed to be 15 trees per acre over 8000 acres, or 120,000 trees total.

Longleaf Pines (95+ Years). The LLPs over 95 years have a dbh over 20 inches with an average dbh of 22 inches. These trees are also acceptable for foraging and artificial cavity construction. LLPs in this age group are acceptable for natural cavity construction by the RCWs. LLPs over 95 years are only removed from the system by their mortality rate and a mechanical removal rate (thinning/harvesting). The mortality rate consists of natural mortality, percentage of deaths to trees due to burning, Ips Beetle infestation, and southern pine beetle infestation. The ideal LLP density for the over 95 years population is assumed to be 10 trees per acre over 8000 acres, or 80,000 trees total.

Turkey Oaks. The turkey oak stock includes turkey oaks of all ages, with an average dbh of 4 inches. Turkey oaks have a germination rate, a mortality rate, and a mechanical removal rate. The mortality rate consists of natural mortality and percentage of deaths to trees due to burning. The ideal turkey oak population is assumed to be 50 trees per acre over 8000 acres, or 400,000 trees total.

Tree Germination. Shading by living trees is assumed to affect the successful germination of both LLPs and turkey oaks. This is a factor that varies form 0 to 1 based upon the density of turkey oaks and of LLPs, with turkey oaks having the greater impact on shading (maximum value of 0.7), while the LLPs have less of an impact (maximum value of 0.3). LLP shading is a function of LLP density and is represented graphically in the model. Turkey oak shading is a function of turkey oak density and is also represented graphically in the model.

Longleaf Pines. The LLP germination rate is a function of the total number of LLPs and the total shading, which is determined by the total number of trees per acre. Germination rates are higher when more sun is available as indicated graphically in the model.

Turkey Oaks. Turkey oak germination is a function of the total number of live turkey oaks and the total shading, which is determined by the total number of trees per acre. Germination rates of turkey oaks are assumed to be not as drastically affected by shading as are LLPs, as indicated by the graphical representation in the model. It is assumed that 67% of the turkey oaks that die as a result of burning will re-sprout.

Tree Health. Tree health for each group of LLPs varies with the burn health, the mechanical removal health, and the basal area health for each group of LLPs, weighted 0.1, 0.3, and 0.6, respectively. The burn health for each tree group is a function of the burn time, which increases from 0 to 1 as the years between burns (burn time) increase from zero to a maximum of ten years (this reflects the fact that burning has some negative impact on tree health). The burn time is set at a constant value of four years, but can be altered to explore different management practices. The values are similar for each group of trees. The mechanical removal health is a function of the removal rate per area for each group of trees, which is discussed in the mechanical removal section, and is represented graphically in the model for each LLP tree group. The basal area health for each age group decreases as the total basal area per acre increases for each LLP tree group, as represented graphically in the model (this recognizes the fact that the health of individual trees is negatively impacted as total tree density increases, due to root competition for nutrients and water).

Tree Mortality.

Natural mortality. For the LLPs, natural mortality for each tree group varies inversely with total tree health for each tree group, as represented graphically in the model.

Percentage of Deaths to Trees due to Burning. The percentage of trees in each age group that die directly from burning is a function of the fire intensity, as represented by graphs in the model, with the LLPs resisting fire more as their age increases. More turkey oaks burn as the fire intensity increases. All graphical representations came from Shaw AFB personnel.

Fire Intensity. The fire intensity is a function of the level of fuel and the stem density fire factor, each weighted equally. If there has been fire management in the past, then the intensity will never exceed 0.75, otherwise it can vary from 1 (plentiful fuel and a thick forest), to 0 (no fuel and an ideal density.)

Stem Density Fire Factor. The stem density fire factor is a function of the stems density fire factors of the four LLP groups multiplied by their respective burn weights, which are 0.5 for the 1 to 30 group, 0.3 for the 30 to 60 group, and 0.2 for 60 to 95 group and the 95+ group combined. As represented graphically, each tree group stem density fire factor increases as the tree group stem density per acre increases.

Fuel. The level of fuel includes the fuel from both turkey oaks and LLPs (multiplied by the time between burns), weighted 0.33 and 0.66, respectively. An increase in the entity "burn time" reflects an increase in the time between burns. LLP fuel level increases as the LLP basal area increases, as represented graphically in the model, where basal area is the stem count per acre times the average radius squared times π. Turkey oak fuel level also increases as the turkey oak basal area increases, as represented graphically in the model, where again basal area is the stem count per acre times the average radius squared times π.

Ips Beetle Infestation in Longleaf Pines. Ips beetle infestation decreases as the total tree health for each group of LLPs increases, as represented graphically in the model. When the total health varies from 0.2 to 1, the Ips beetle infestation factor varies from 0.02 to 0.002. Beetle infestation rates are approximately the same for each tree age category.

Southern Pine Beetle Infestation in Longleaf Pines. The southern pine beetle infestation decreases as the total health for each group of LLPs and is indicated graphically. When total health is 0, the infestation rate is 0.905. The rate drops off until it reaches 0 when total health equals 0.4. The rate remains at 0 while the total health varies from 0.4 to 1. Beetle infestation rates are the same for each tree age category.

Tree Mechanical Removal. The mechanical removal rate for LLP represents thinning for pulpwood, while for the turkey oaks it represents clearing all hardwoods in the area. It is assumed the trees with weaker health will be removed, and any removal will increase the health of the entire stand. The removal rate is the excess trees divided by the time between thinning, which is set at eight years for the LLPs and four years for the turkey oaks. The excess trees are the difference between the ideal stem density and the actual stem density. Note that if the ideal is greater than the actual, then no mechanical removal will occur.

Cavity Sector Model Structure

The basic structure of the cavity sub-model is a set of four stocks representing all cavity trees. These stocks are acceptable and available cavities, RCW occupied cavities, flying squirrel occupied cavities, and unacceptable cavities due to enlargement by pileated woodpeckers. The combined total of each of these stocks yields the total number of cavities which is initially 87, based on information from Shaw AFB. The total number of cavities can be reduced only through cavity tree mortality.

The loss of cavity trees is based upon the increased mortality of LLPs due to the weakening of the infrastructure as a result of cavities. The literature indicates that the cavity tree mortality rate is 0.013 deaths/tree/year (Conner and others, 1991:534-536). This cavity tree loss is inclusive for all four stocks of cavities and is slightly higher than the mortality rates of LLPs without cavities. The cavity tree mortality rate cannot be used as a constant but instead must represent the increased mortality of cavity trees versus normal LLPs. The LLP mortality rate is essentially the literature based mortality rates of two stocks of cavity-free trees weighted by their population to provide a representative mortality rate of all the mature trees in the model. After determining the mortality rate of LLPs over 60 years old as a result of natural and human generated events in the tree sub-model, we augment this with an increased mortality rate representing increased cavity tree susceptibility. The mortality rate of both LLPs and cavity trees can be found in the literature. The difference gives us a “delta” which can augment the LLP mortality determined in the tree sub-model. As a result, this cavity tree mortality rate should mimic the ill effects placed upon the trees in the tree sub-model due to beetle infestation, fire, wind snap, and so forth, but with slightly increased mortality due to increased cavity tree susceptibility.

Acceptable and Available Cavities. Initially there are 54 acceptable available cavities. More cavities are created at a construction rate based on pioneering and artificial cavity construction. Artificial cavity construction accounts for up to 20 cavities per year if the number of available cavities is low. Pioneering accounts for up to 3 cavities per year if the number of available cavities is low. Both rates decrease if the tree density falls below the optimum of 60 to 80 square feet per acre. The construction rate is never allowed to exceed the number of LLPs available, whether it is LLPs 60 years and older for artificial cavity construction or LLPs 95 years and older for natural cavity construction. Available cavities are lost to cavity tree mortality, RCW or squirrel occupancy, and to enlargement.

RCW Occupied Cavities. Twelve cavities are initially occupied by RCWs based on figures from Shaw AFB. Cavity occupancy increases and decreases as the adult RCW population changes each year. Fledglings are not considered to occupy their own cavity since they share a cavity with a parent. Thus, only one through six year old birds can change the number of RCW cavities occupied. However, overall cavity occupancy is not solely based on RCWs but also includes competitor occupancy.

Flying Squirrel Occupied Cavities. Initially, 20 cavities are occupied by flying squirrels, based on data from Shaw AFB. Squirrel occupancy changes based on the change in overall squirrel population multiplied by the fraction of squirrels which occupy RCW cavities less the amount of squirrel boxes installed.

Competitor Population Growth. The inflow for the competitor stock is controlled by the competition birth rate (the number of squirrels born per year) and is the product of the number of competitors times the birth rate of two pups per squirrel. The birth rate was calculated per squirrel by taking the literature value of five pups per year, dividing by two to account for the number of squirrels per breeding pair, and then multiplying by the fraction of squirrels of breeding age (4/5 or 80%). Since the squirrels are not assumed to be controlled by top down predation, the availability of food is believed to affect squirrel birth rates. Therefore, a food factor is used as a multiplier for the overall birth rate. The food factor is represented graphically in the model and ranges from zero (where the food per squirrel value is zero) to one (where the food per squirrel value is 20). The turkey oak basal area divided by the competitor stock is used to represent the availability of food per squirrel.

Competitor Population Decline. The outflow of the competitors stock is a sum of the number of squirrels captured per year plus the number of competitors lost each year due to predation and mortality. The predation and mortality rates are multiplied by the number of competitors in the stock. The mortality rate is set at 0.5 and is multiplied by the mortality switch (1=on; 0=off), which allows the mortality rate to be turned either on or off. The predation rate is represented graphically and ranges from one, when there are no turkey oaks to provide cover from predation, to near 0.01, when there are enough turkey oaks to provide cover from predation. The capture rate is also represented graphically, and ranges from 0, when there are only 20 cavities occupied by squirrels, to 100, when there are 100 cavities occupied by squirrels.

Competition Pressure. The competition pressure (in squirrels/year) is the net number of increase in squirrels per year that would be looking to occupy a cavity. It is calculated by taking the difference between the squirrel birth rate and the loss rate and then multiplying this difference by the fraction of squirrels that choose to live in cavities versus building their own den. Finally, the squirrels that occupy the squirrel boxes are subtracted to provide the final value for competition pressure.

Unacceptable Cavities. There are initially 20 unacceptable cavities due to enlargement by pileated woodpeckers. This stock is influenced by the rate of metal restrictor plates installed and the rate of enlargement by pileated woodpeckers. Once a restrictor plate is installed, the cavity is considered available and acceptable again. The enlargement rate begins at 0.0318 enlargements/tree/year (Conner and others, 1991:535). This rate decreases as the rate of restrictor plate installation increases. This is based on the assumption that cavities with restrictor plates cannot be enlarged.

Red-Cockaded Woodpecker (RCW) Sector Model Structure

The RCW sub-model attempts to model the significant entities and relationships influencing the RCW population while utilizing a basic life span structure for the RCW. The sub-model focuses on the influences which affect the birth, death, and departure rates of the RCW population. The RCW population is also dynamically affected by the adequacy of its foraging area and the number of available cavities per cluster. In many cases, the foraging area and the number of available cavities will be the limiting factor for the RCW population. The limitations to the RCW population presented by foraging area and available cavities is defined in the tree and cavity sub-models. The number of breeding pairs, the foraging area, and the number of helpers per breeding pair are the factors assumed to be most influential in the population's birth rate based on the literature review. The death rate is assumed to be driven primarily by natural mortality and predation while the departure rate can fluctuate due to the absence of a mate, lack of adequate clusters, lack of acceptable cavities, and lack of adequate foraging area.

RCW Key Entities and Relationships.

Breeding pairs. Breeding pairs are a function of the number of males and females and the availability of cavities per cluster. It is assumed only one breeding pair will occupy a cluster. The sub-model determines the potential number of breeding pairs by pairing each male RCW of breeding age to a female RCW of breeding age. It is assumed that birds matched for breeding are unrelated. A breeding pair will stay in the managed area only if there are two acceptable and available cavities in a cluster the pair can occupy; otherwise, the female RCW will depart and the male RCW will remain in the area to become a helper (if there are an adequate number of cavities). It is apparent that the RCW population birth rate will increase with the number of breeding pairs.

Helpers per breeding pair. It is assumed in this model that only males of breeding age without a mate are eligible to become helpers. If a male RCW does not have a mate, the male will become a helper only if an adequate cavity is available within a cluster. Otherwise, the male RCWs is assumed to depart the managed area.

The fledgling mortality rate is assumed to equal the natural mortality rate of fledglings when the breeding pair has no helpers. The fledgling mortality rate will decrease as the number of helpers per breeding pair increases. The decrease in the mortality rate will remain constant when each breeding pair has an average of four or more helpers.

Foraging area. Foraging area is defined in this model as the basal area of LLPs 30 years and older within the area of management concern. Each individual RCW requires a certain basal area to provide its nutritional requirement of insects. The quality of the foraging area is determined by comparing the required basal area per bird with the actual basal area per bird. The foraging area is assumed to be adequate if the actual basal area per bird equals or exceeds the minimally required basal area.

It is assumed that a minimum area of foraging area is required to produce the "normal" amount of fledgling per breeding pair. If the available foraging area exceeds this amount, the birth rate is not effected; if the foraging area is less than the minimum required, the production rate of each breeding pair diminishes.

The foraging area will also influence the departure rate of the RCW from an area of management concern. Poor foraging area will enhance the departure rate of breeding age males and females from the area of management concern. Adequate foraging area will not necessarily prevent birds from departing; RCWs will still depart due to a lack of a mate or lack of an acceptable cavity.

Mortality Rate. The mortality rate applied to the RCW population includes the effects of predation, disease, strafing deaths, and natural mortality. The mortality rates for the male and female fledgling stock are decreased by the number of helpers per breeding pair which is less than four.

Departure Rate. The total number of male and female RCWs departing an area of management concern are represented by two separate entities. The number of birds departing are divided equally over the respective stocks representing the male and female RCWs of breeding age.

The female departure rate is determined by the availability of a mate and the availability of adequate cavities. Additionally, the female departure rate can increase due to inbreeding aversion represented by a relatedness factor which is described in the RCW Model Limitation section. Male RCW departure is influenced primarily by the availability of adequate cavities. Poor foraging area will accelerate both the female and male departure rates.

RCW Model Limitations. Simplifying assumptions were required to model the mechanisms driving the changes in an RCW population. These assumptions were necessary in order to capture the essence of the complex social structure, breeding activity, and foraging habits of the RCW. Many of the mechanisms associated with the birds behavior such as the female RCW's instinct to depart rather than inbreed and the RCW's decision to depart an area rather than stay and foray are not well understood. However, entities representing these behavior patterns have been incorporated in the model with simple mechanisms to ensure these important influences on the RCW population are addressed accordingly. These limitations will also be discussed in the "Model Strengths and Weaknesses" section of Chapter 5.

Incest Avoidance and Loss of Genetic Diversity. As stated previously, it is assumed in the model that the number of new breeding pairs within an area of management concern is dependent solely upon the availability of a mate and the cavity availability for a breeding pair. The assumption that female RCWs will stay within a managed area as long as they can find a mate is accurate as long as there is an abundance of unrelated birds. Typically, female RCWs will depart its cluster to find an unrelated male for a mate rather than inbreed. The incest avoidance instincts of the female RCW makes inbreeding among RCW separated by a single generation rare. However, inbreeding among distant relatives is not unlikely, particularly when the RCW population is isolated. Inbreeding would attribute to a population's loss of genetic diversity; consequently, the fertility rate of an RCW population may be adversely affected if extensive inbreeding occurs.

Relatedness Index. The influence of the female RCW's instincts to avoid inbreeding is represented by the entities "Relatedness" and "Relatedness Index". The two entities define the general relationship expected between the RCW population size and the tendency for a female RCW to depart an area due to its incest avoidance instincts. It is assumed that as the RCW population decreases, the percentage of genetically related male and female RCWs will increase. The percentage of genetically related males and females will be minimized as the total RCW population exceed 25 birds. Consequently, the female RCW departure rate will increase as the RCW population decreases over an extended period (when the total RCW population is less than 25 birds).

Genetic Diversity Loss. In small and isolated RCW populations such as Poinsett Range, the likelihood for inbreeding increases. Intuitively, extended periods of inbreeding may diminish the fertility rate of breeding pairs, increase the mortality rate of fledglings, and diminish the RCW population's ability to combat certain diseases. The effects of extended interbreeding on the RCW population is not addressed in the model.

Artificial Translocation. Artificial translocation is a management practice which brings RCWs from areas outside a particular managed area into the managed area. This management practice may be used to enhance the genetic pool of an RCW population or to increase the number of breeding pairs in the area. At the Poinsett Range, the RCW population is isolated, and the active clusters within the range consist of birds that are related. This situation suggests that artificial translocation is necessary in order to sustain the RCW population. Some efforts at artificial translocating birds into the Poinsett Range have been made, although the success of this action has not yet been determined.

The translocation of birds is represented in this model through an additional inflow of birds into the stocks of females and males one through three years of age. It is assumed in this model that only younger male and female RCWs of breeding age would be transplanted into the area to maximize the available number of breeding years and minimize mortality. In the baseline runs of the model, the artificial translocation rate for both male and female birds are set to zero. Translocation of birds out of the area is not considered in this model.

Foraging Area and the Effect on Immigration and Emigration. It is assumed the RCW will depart the area of management concern at an accelerated rate if the foraging area is below the minimum area necessary to meet each bird's nutritional requirement of insects. The model assumes the managed area is contiguous to suitable RCW habitat which can provide the necessary basal area, and the natural immigration rate of birds into the managed area is negligible.

Overall Model Interaction

Although each sector represents a separate critical piece to the overall Poinsett Range ecosystem, the junction points connecting each sector of the model prove critical in establishing the overall behavior of the ecosystem. The tree sector determines how many cavities can be constructed and how many cavities remain acceptable and available for use. The cavity sector distributes the number of cavities appropriately based on competitor and RCW levels while accounting for those cavities lost to cavity tree mortality and unacceptable cavities. Moreover, the cavity sector ultimately determines the allowable number of clusters available for the RCW. The RCW population can fluctuate based on cavities and cluster numbers as well as foraging area. These links between the sectors are crucial to the model's ability to mechanistically represent the behavioral trends of the Poinsett Range ecosystem.

V. Model Testing and Discussion

With the model constructed, simulations were completed for comparison to the reference mode and sensitivity analysis. Initially, the model's parameters are set to reflect conditions parallel to the current conditions at Shaw AFB including the management practices now being utilized in managing the Poinsett Range. The model, if accurate, should give results similar to the reference mode which represents a hypothesized representation of the behavior of the real world system at Shaw AFB. The hypothesized reference mode chosen for the project simply depicts behavioral trends for various indicator species of a longleaf pine (LLP) ecosystem which stabilize to positive values over time. Figure 1 illustrates this reference mode for the project.

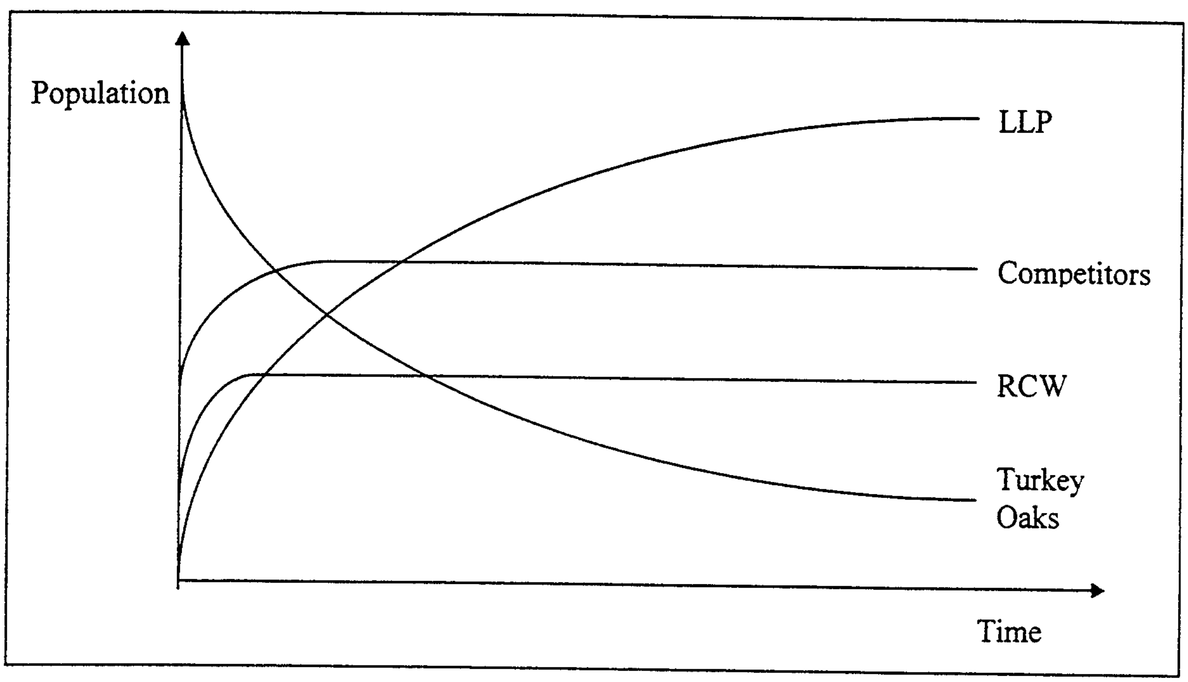

Figure 1. Hypothesized Reference Mode

Current Management Practices - Baseline Output

The baseline populations of indicator species shown in Figure 2 represents initial output from the model with the parameters set to reflect current management practices and will be used as the baseline for exploring the effects of the various management practices and other client driven scenarios such as catastrophic events (All relative output and discussion for the various scenarios can be found in Chapter 6 - Alternative Management Scenarios and Recommendations.).

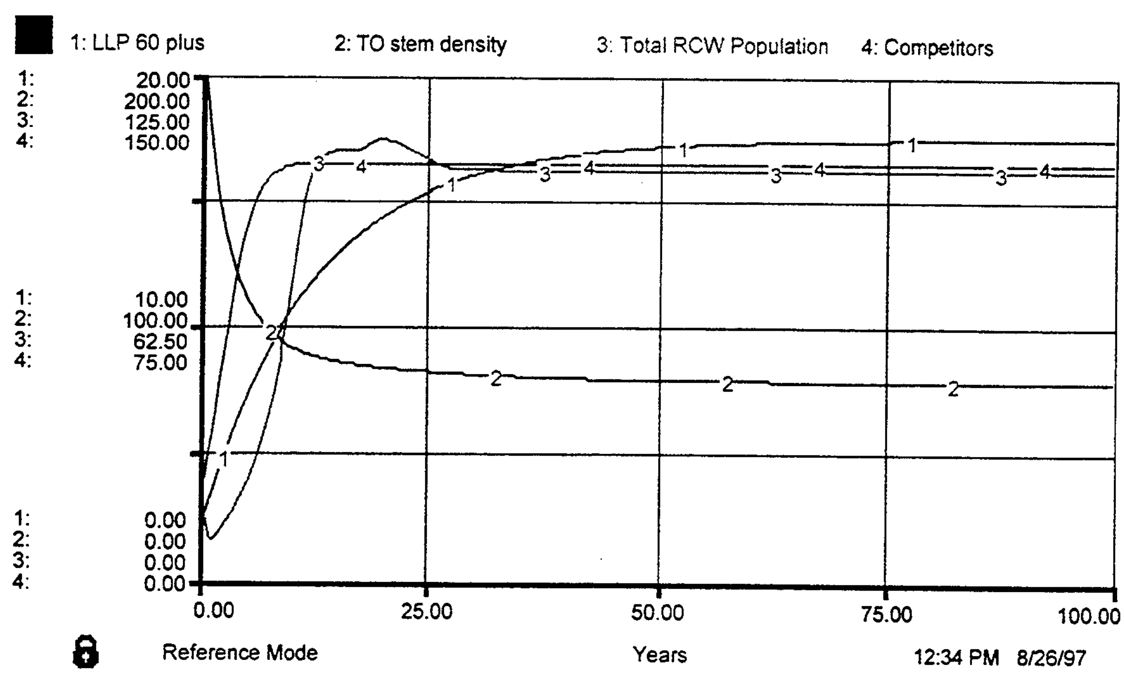

Figure 2. Baseline Output with Current Management Practices.

With current management practices in place (Figure 2), all the indicator species studied reach a steady state after about 25 years, except for the mature LLPs which take about 50 years to reach steady state. All the desirable species in a LLP ecosystem increase to a steady state level except turkey oaks which decrease to a lower steady state level. Comparing Figure 2 to the hypothesized reference mode,

Figure 1, one can conclude the basic mechanisms of the constructed model create the reference mode; therefore, it appears the overall dynamic hypothesis of the Poinsett Range system has been successfully modeled.

Validation Testing

Model testing must also incorporate testing model assumptions to ensure the model includes the important variables, the assumed relationships are reasonable, and the parameter values are plausible. Because system dynamics modeling concentrates on overall system trends instead of predicting precise numbers, standard statistical tests are not used to validate the systems dynamics model structure (Forrester, 1996:421). Confidence was gained in the model through iterative inspection and use by the client and through the application of five validity tests: Structure Verification, Parameter Verification, Extreme Conditions, Boundary Adequacy, and Behavior Anomaly.

<u>Structural Verification</u>. First the structure and influences were developed from and compared to the mechanisms discovered during the literature review. Further structural verification was performed by comparing the actual structure of the model with the structure of the real world system. Moreover, by explaining the detailed model structure to the client, the team and client were able to ensure the model structure was reasonable, there were no contradictions between the model and the real world system, and the assumptions in the model were valid. The structure of the model was revised through an iterative process based on discussions with the client during the three field trips to Shaw AFB.

Parameter verification. Parameter verification was conducted conceptually by reviewing the parameters with the user to ensure the parameters encoded in the model actually existed and matched elements in the real system. The numerical values and ranges of the parameters were reviewed with and verified by the client.

Extreme Conditions. The model's behavior under extreme conditions was tested by setting the stocks and rates to realistic real world extreme conditions and observing the behavior of the model. It was important that the model did not crash or that the responding behavior seemed realistic and was explainable. The section "Sensitivity Analysis" of this chapter presents a more detailed discussion of using extreme conditions for model testing.

Structural Boundary Adequacy. Structure Boundary Adequacy was validated by explaining to the client the aggregation of real world influences incorporated into the system dynamics model. The client also reviewed the model to ensure all relevant structure had been included and that no plausible hypothesis could be proposed that indicated the need for additional mode entities or mechanisms. For example, the suggestion that a beaver consumption mechanism be added would not be realistic, since this is not a plausible entity for this system. Behavior Boundary Adequacy was verified by ensuring the addition or removal of model structure did not affect the model's behavior. More time should to be spent testing the model by adding additional structure; however, an example of excessive structure in the model is the tree foraging area mechanism. This mechanism was never activated by the model during testing under extreme conditions, and could be removed without affecting the behavior of the model.

Behavior Anomaly. Behavior anomalies, such as stocks or rates remaining constant or changing erratically during the model simulation, were observed during the initial coding and running of the model. This often indicated the model needed revision so the model more accurately reflects the mechanisms of the real world system. The model was also tested to see if it showed implausible behavior when the assumptions were altered. Surprise behavior, when an unnoticed behavior of the real system surfaces, was also discovered. For example, translocation of the RCWs does not produce a higher population than natural population growth. This may seem counterintuitive, until it was considered that the birds were introduced into the system too quickly before acceptable cavities could be prepared for them. As a result, the homeless translocated RCWs would leave the system.

Sensitivity Testing

By varying different parameters in the model through extreme values, an indication of their significance to model output was established. This process of sensitivity testing allows modelers to identify parameters which are the most sensitive and others which are not. Sensitive variables can then be closely scrutinized to ensure their input values are accurate.

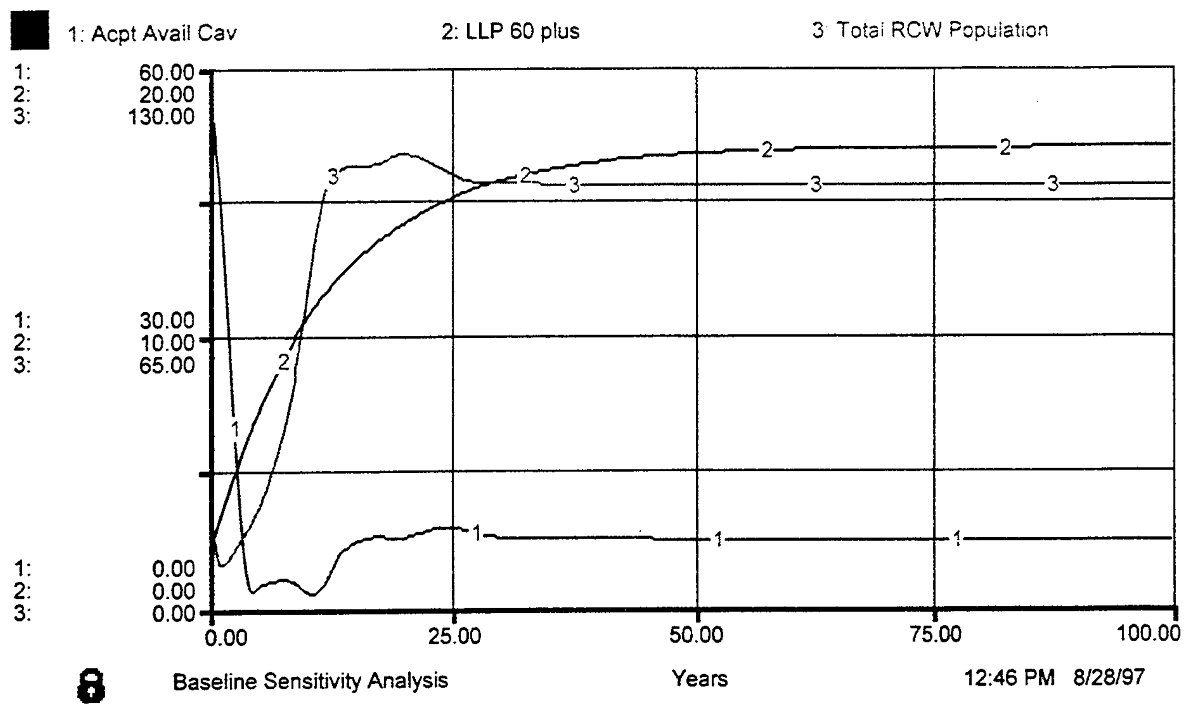

Figure 3. Baseline Sensitivity Analysis Graph.

Baseline Output for Sensitivity Analysis. Baseline values for the sensitivity analysis are portrayed in Figure 3. The acceptable available cavities decrease as RCWs and squirrels occupy them. The decrease is also a result of the artificial cavity construction rate not increasing quickly enough to counteract the RCW and squirrel occupancy. Ultimately, a lower steady state value is reached.

Acceptable Cavities. The first area of sensitivity testing was with acceptable cavities. Tests were made on the number of acceptable cavities with varying artificial cavity construction rates, initial squirrel populations, RCW pioneering rates, and cavity opening enlargement factors.

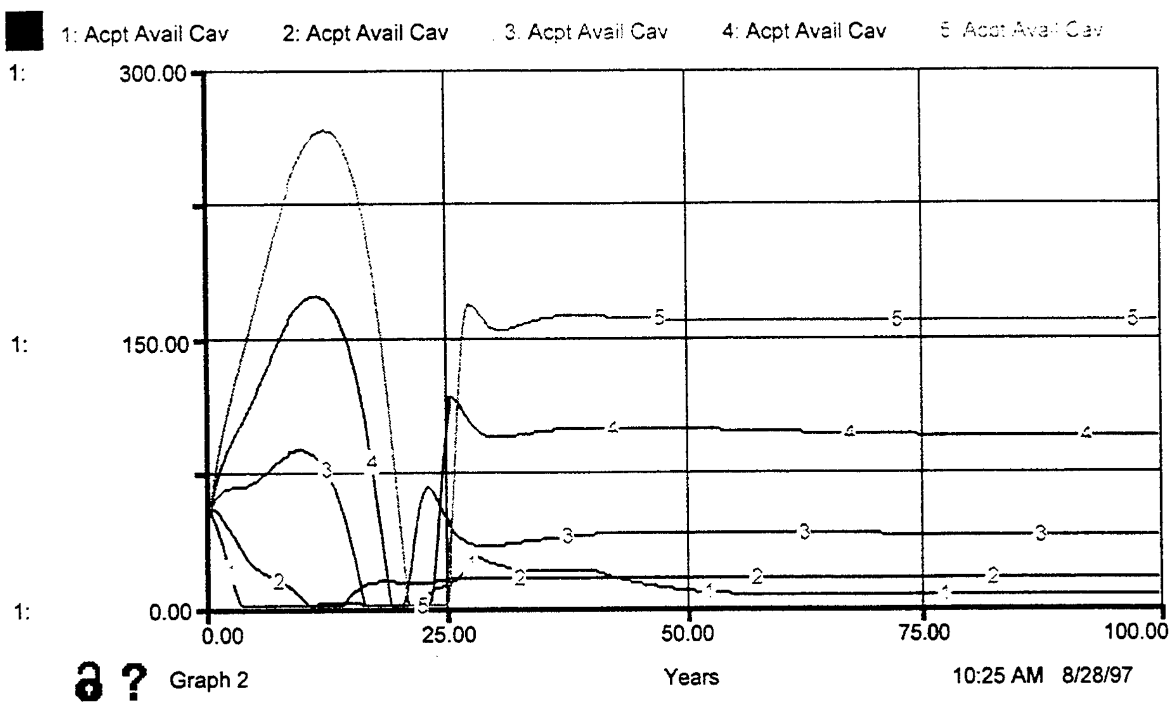

Figure 4. Acceptable Cavities with Variation of Artificial Cavity Construction Rates

In Figure 4, the artificial cavity construction rate was varied from 0 to 50 in five runs, 0, 12.5, 25, 37.5, and 50, respectively. Traces 1 and 2 show artificial cavity construction and pioneering rates are less than the loss rates of acceptable cavities through enlargement, squirrel occupancy, and loss of cavity trees. This causes the initial drop in acceptable available cavities. In traces 3, 4, and 5, the construction and pioneering rates exceed the loss rates so the traces show an initial increase. The squirrel population initially increases dramatically in our model due to the high turkey oak stem count. The turkey oak stem count rapidly drops through management practices (See Figure 13 in Chapter 6) which in turn causes the squirrel population to overshoot and collapse due to the reduction in food production by the turkey oaks. During the overshoot phase, the acceptable available cavities go to zero in all the scenarios. After the squirrel population collapses, the cavity construction rate exceeds the squirrel occupancy rate, and the acceptable available cavities increase in all traces.

This rate increases so fast that the trace overshoots the equilibrium value before settling into its equilibrium. It should be noted that trace 2 does not show this overshoot behavior. It is felt this effect is not prevalent in trace 2 because the artificial construction rate is at 12.5, which is very close to the equilibrium construction rate for the baseline model (See Figure 3). From this test it is apparent that the number of acceptable cavities are sensitive to the artificial cavity construction rate.

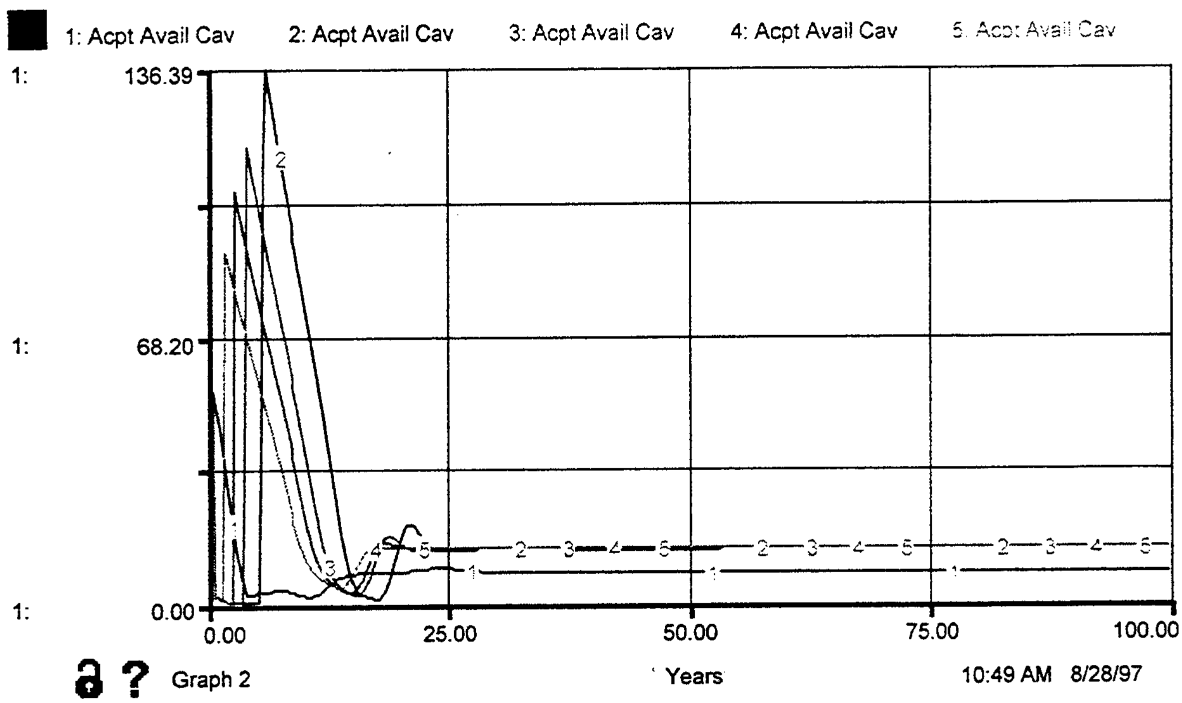

Figure 5. Acceptable Cavities with Variation of Initial Squirrel Population

In Figure 5 the initial squirrel population was varied from 30 to 30,000, traces 1 to 5, respectively. All traces show an initial decrease due to the rapid occupancy of cavities by squirrels. As stated before, the turkey oak stem count starts at a high value, which causes the squirrel population to increase dramatically. After the turkey oak stem count decreases through management techniques, the squirrel population overshoots and collapses. This again results in an increase in the acceptable available cavities in traces 2 to 5. The artificial cavity construction rate is constant in this scenario, so with increasing initial populations (traces 2 to 5), the acceptable number of cavities decreases with increasing initial squirrel populations (the artificial construction rate cannot keep up with the occupancy rate). This behavior is not found in trace 1 due to the small initial squirrel population, which never has the opportunity to overshoot its food base (acorns from the turkey oaks). Traces 2 to 5 go to the same steady state since the squirrel population is controlling the system and are therefore causing the artificial cavity construction rate to reach a higher equilibrium. Trace 1 falls to a lower equilibrium since the squirrel population is not driving the artificial cavity construction rate. Upon reaching equilibrium, the values are very close, so this parameter is not judged as sensitive.

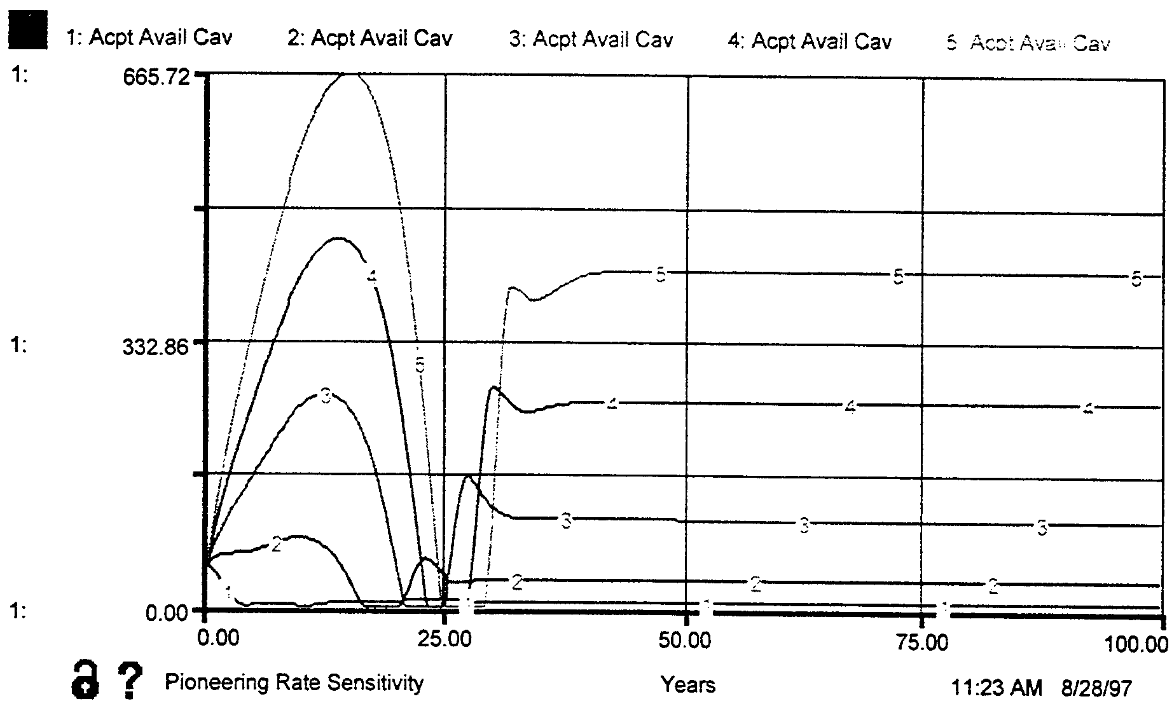

Figure 6. Acceptable Cavities with Variation of Pioneering Rates

In Figure 6, the pioneering rate was varied from 0 to 100 in five runs, 0, 25, 50, 75, and 100, respectively. This output is very similar to Figure 4. In trace 1, the pioneering and artificial cavity construction rates are less than the loss rates. This causes an initial drop in acceptable available cavities. In traces 2 to 5, the pioneering and construction rates exceed the loss rates so the traces show an initial increase. As demonstrated previously, the squirrel population overshoots, causing acceptable available cavities to go to zero. After the squirrel population collapses, the pioneering rate exceeds the squirrel occupancy rate, and the acceptable available cavities increase in all traces. This rate increases so fast that the trace overshoots the equilibrium value before settling into its equilibrium. From this test it is apparent that the number of acceptable cavities are sensitive to the pioneering rate.

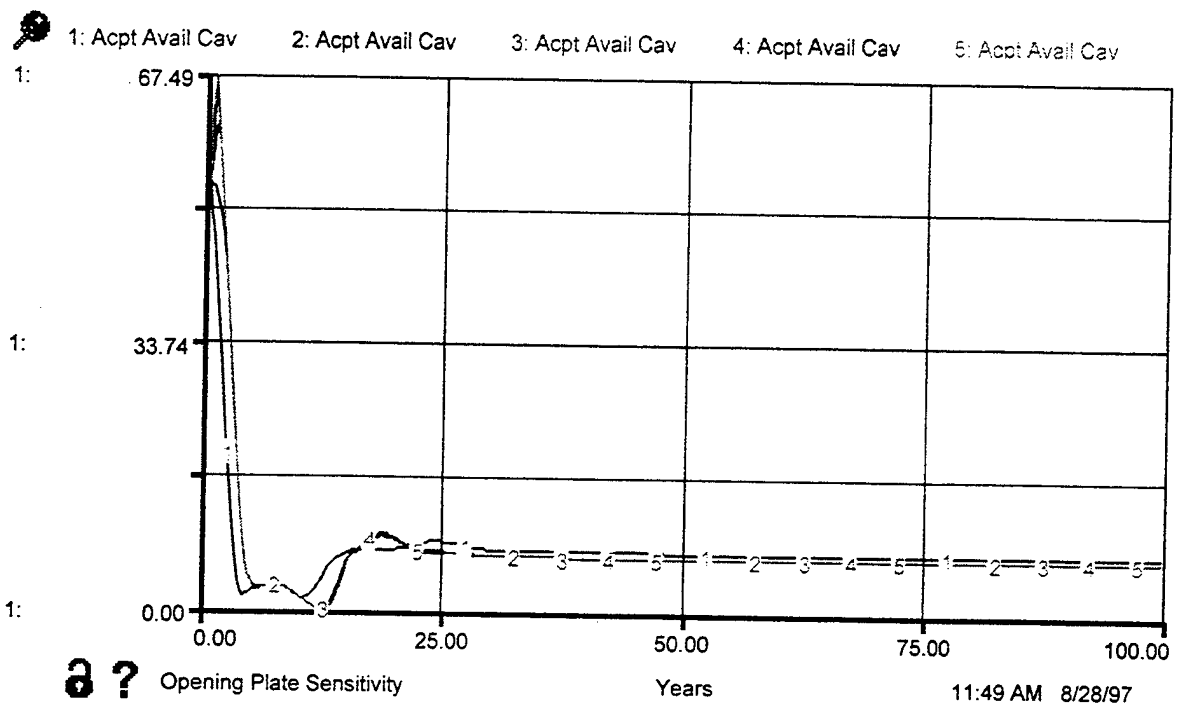

Figure 7. Acceptable Cavities with Variation of Opening Plate Construction Rates

In Figure 7, the opening plate installation rate was varied from 0 to 100 in five runs, 0, 25, 50, 75, and 100, respectively. All values quickly approach an equilibrium value of approximately 7.5. The opening plate installation rate has an inverse linear relationship with the pileated woodpecker enlargement rate. Both these values feed into the occupancy rate and are additive. Because of the additive and inverse linear relationship, their sum always comes out the same. This in turn gives the same result for the sensitivity analysis; therefore, the opening plate installation rate is not a sensitive variable.

Longleaf Pines. The second area of the sensitivity test deals with the longleaf pine entity, specifically relating longleaf pine to burn times and mechanical removal rates. However, this type of testing is considered management testing and will be covered in the management analysis in chapter 7. A test was performed on the longleaf pine mature stem density with varying artificial cavity construction rates.

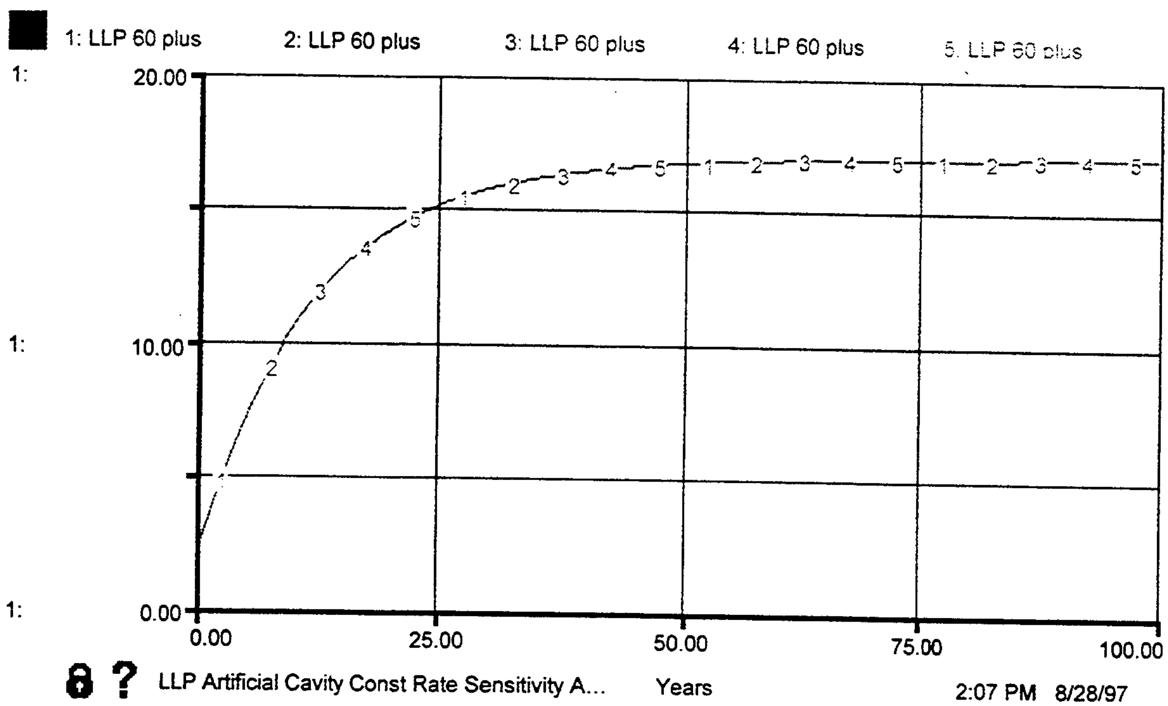

Figure 8. Longleaf Pine with Variation of Artificial Cavity Construction Rates

In Figure 8, the artificial cavity construction rate was varied from 0 to 50 in five runs, 0, 12.5, 25, 37.5, and 50, respectively. As expected, the installation of artificial cavities does not affect the mature longleaf pine population significantly. Though trees with artificial cavities do have a higher mortality, the number of these trees is small in comparison to the total mature tree population, making this mortality increase insignificant. This longleaf pine population is definitely not sensitive to the artificial cavity construction rate.

RCW Population. The third area of sensitivity testing involved the RCW population. Tests were made on the RCW population by varying birth rates, relatedness, foraging area, and artificial translocation rates.

Factors such as stress or intergenerational inbreeding may affect the birth rate of the RCW population. In the following sensitivity test, it was assumed that the birth rate would be less than the birth rate of a healthy RCW population. The sensitivity of the total RCW population was tested by defining the birth rate as a constant (Figure 9).

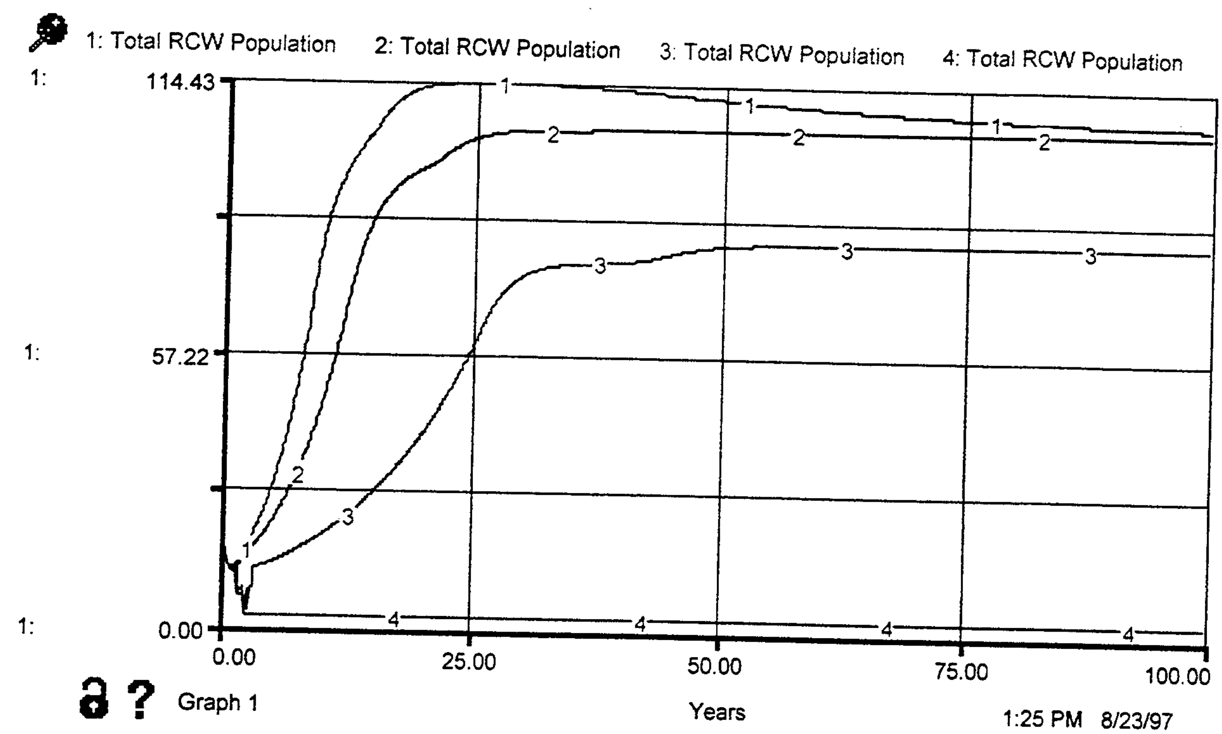

Figure 9. RCW Population Sensitivity to Birth Rate

In Figure 9, the birth rate was varied from 1.25 to .5 in four runs, 1.25, 1.00, .75, and .5, respectively. Trace 1 is at baseline conditions and levels off at the highest stable population level of the graph. Traces 2 and 3 show the RCW population stabilizes at a lower level than the baseline condition. It is apparent at a birth rate of .5 (trace 4) that the RCW population cannot sustain itself. When the birth rate changes from .75 to .5, there is a marked change in the RCW population. At higher birth rates, the limiting factor is most likely the availability of cavities, while at lower birth rates, RCW departure becomes the main influence. The RCW population is extremely sensitive to this parameter in the range from .5 to .75; therefore, exact birth rates are necessary for RCWs.

The next sensitivity analysis tests how the RCW population is affected by the relatedness entity. The relatedness entity is defined with the assumption that as an RCW population reaches a certain number, the individual birds within the population will become less related; this specifically applies to how related a female RCW is with the male RCWs in the population. In the baseline run (Figure 10, trace 2), it is assumed that as the RCW population approaches 25 members, a female RCW will not depart an area of management concern due to its incest avoidance instincts.

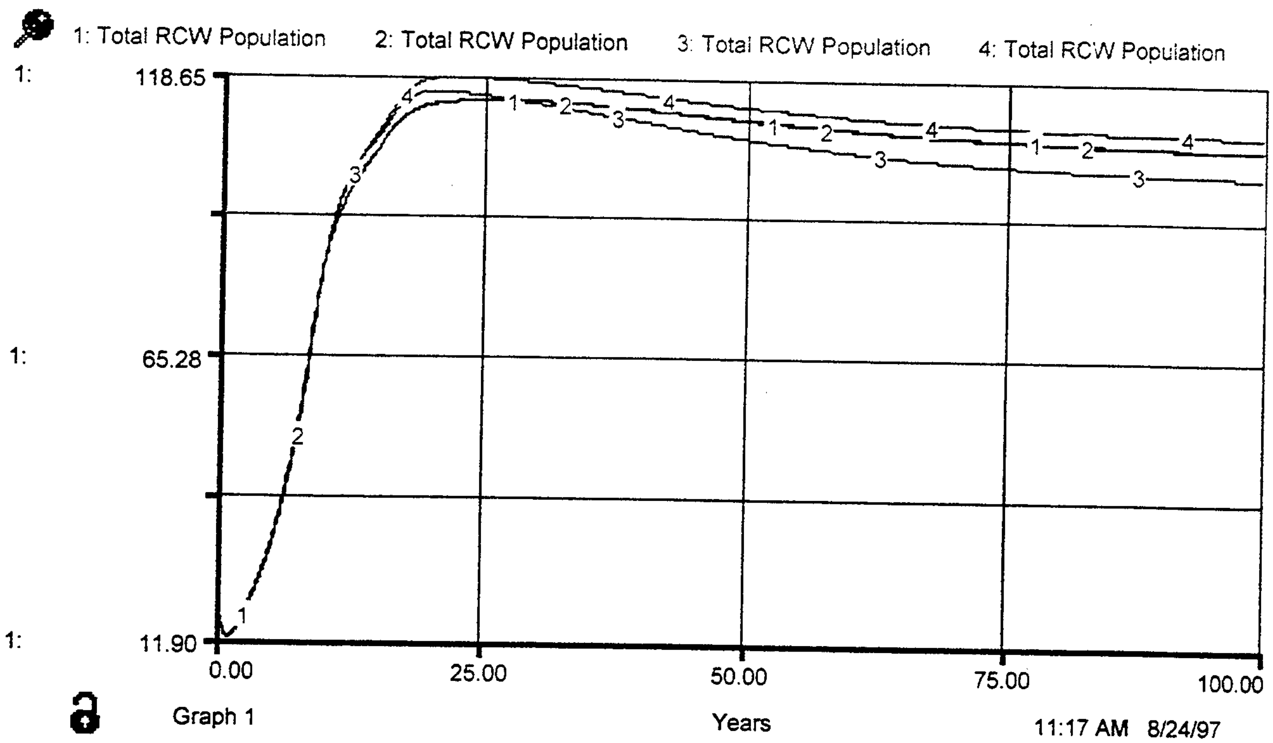

Figure 10. RCW Population with Variation of the Relatedness Entity

In Figure 10, the relatedness entity was varied from 5 to 100 in four runs, 5, 25, 100, and 200 members, respectively. Traces 1 and 2 represent RCW population behavior when the relatedness entity utilizes lower RCW populations for defining the population at which relatedness is no longer an influence on female departure due to incest aversion. Consequently, the populations represented by traces 1 and 2 do not reach as high a value before reaching equilibrium as compared to traces 3 and 4 which employ higher RCW populations for the relatedness entity in defining the population at which relatedness is no longer an influence. The populations associated with traces 3 and 4 will therefore reach a higher value. The equilibrium values of traces 1 to 4 do not vary to a great extent, so this test deems the relatedness entity as an insensitive parameter.

The entity "required basal area per bird" defines the necessary basal area of LLP 60 years and older to provide the nutritional requirements of each RCW in the area of management concern. The foraging area quality is based on the value set in this entity. The foraging area has a two-fold effect on the RCW population; the foraging area quality will enhance the departure rate of mature male and female RCW and diminish the fertility rate of each breeding pair that remains in the area (Figure 11).

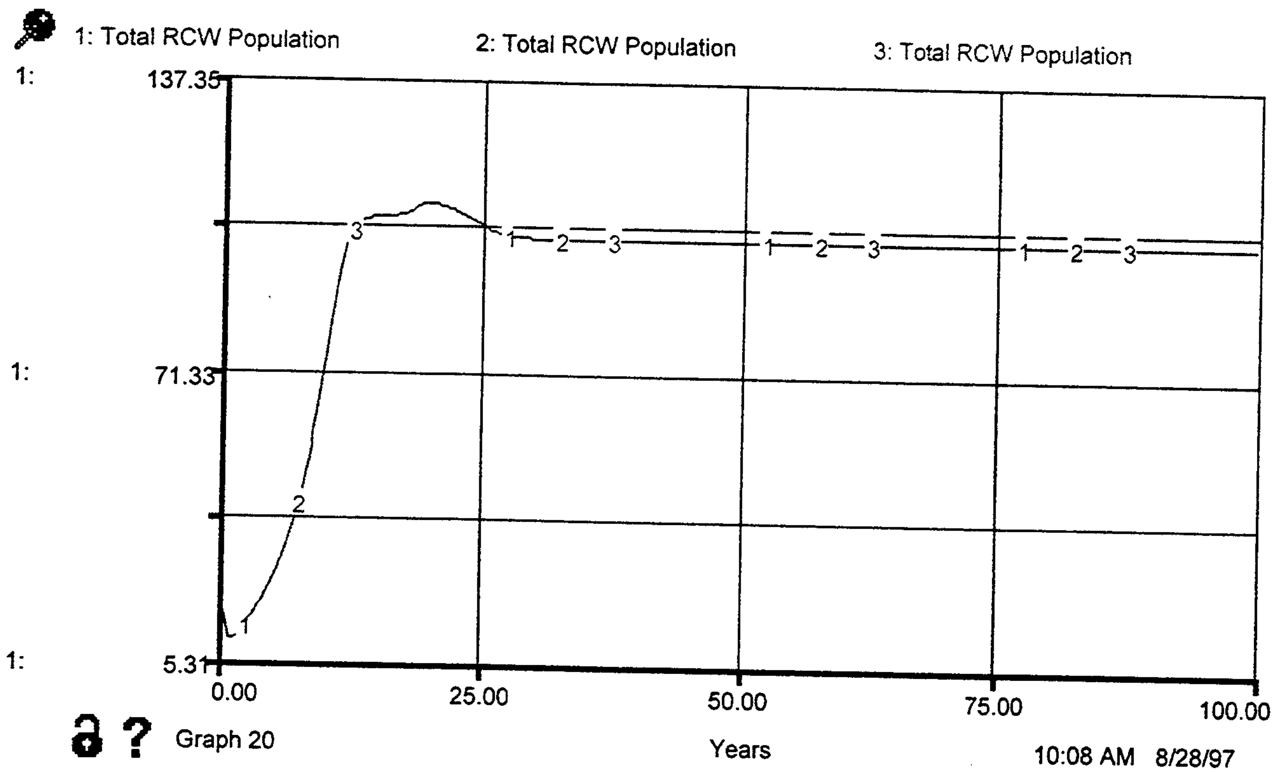

Figure 11. RCW Population with Variation of Foraging Area per RCW

In Figure 11, the foraging area per RCW entity was varied from 1 to 600 in three runs, 1, 60, and 600, respectively. Given that legislation only requires 125 basal area for a cluster, these values cover the expected range of values for this parameter. All three traces are exactly the same; they follow the baseline output. Therefore, RCW population is not sensitive to this parameter.

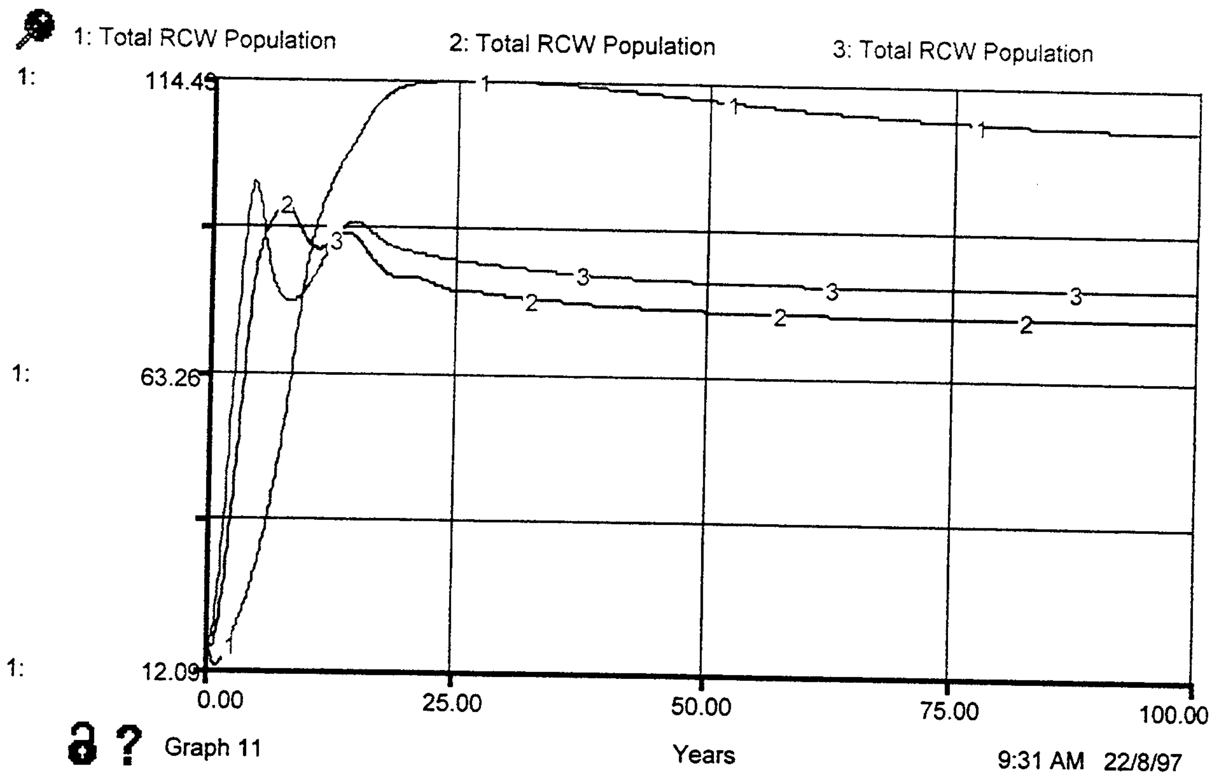

Figure 12. RCW Population with Variation of the Artificial Translocation Rate

In Figure 12, the artificial translocation rate was varied from 0 to 10 in three runs, 0, 5, and 10, respectively. Trace 1 is the baseline condition for the model with a translocation rate of 0. Traces 2 and 3 show a much faster initial population increase because the import rate is at a high value. Both traces overshoot and collapse since the cavity construction rate does not keep up with the translocation rate and the competitor's occupancy of cavities, forcing many of the birds out of the ecosystem. After this collapse, the two traces reach a lower equilibrium level than trace 1. Although initially it seems traces 2 and 3 would reach a higher equilibrium than trace 1, they fail to because RCW population *change* influences RCW occupied cavities and acceptable available cavities which subsequently affect the cavity construction rate. Thus, if the population change is not large enough or is negative, cavity construction slows down even though there may be imported birds in need of a cavity. Traces 2 and 3 reach steady state at lower population levels due to fewer cavities being constructed, a result of the lack of a significant positive population change as seen in trace 1. This sensitivity test shows the RCW population is sensitive to the translocation rate.

Model Strengths and Weaknesses

From the model's initial output, validation testing, and sensitivity analysis, the model's strengths and weaknesses were discovered and then evaluated based on the model's success in answering the research questions posed by the client by running long-range simulations and in helping the client to understand the basic mechanisms driving ecosystem behavior. Recall the research questions focus on the effects of ecosystem management and RCW management practices on the viability of the LLP ecosystem as defined by tree composition, density, and age structure.

Model Strengths. The main strength of the model lies in the model structure which allows for long-term simulations of a wide variety of scenarios important to the interests of the client. These scenarios involve combinations of ecosystem management practices, RCW management practices, and naturally occurring environmental impacts. The output of the model simulations can be used by the client to evaluate proposed management strategies and to prepare for the impacts of naturally occurring events.

The model building process and model simulation output served as an effective aid to the client in developing a deeper understanding of the influences which affect the managed ecosystem and in tying together intuitions about the ecosystem's behavior under various scenarios. The process of constructing the model required the client to examine the entities within the ecosystem, to determine the relationships between each entity, and to weigh and evaluate the influence of each relationship. This process enabled the client to further develop his intuition and understanding with regards to the interrelationships occurring within the managed ecosystem. Through the model building process the client developed a firm understanding of the assumptions used in the model and gained confidence that the model structure incorporated the entities and relationships necessary to answer the research questions. As a result, the client was well qualified to evaluate the validity of the model simulation output.

The model output effectively communicated to the client the potential consequences resulting from various management and environmental scenarios. The graphical output of these simulations served as a convenient way to evaluate the system's behavior under varied conditions. The model output was validated against the client's expectations of the system's behavior under the scenarios tested. Thus, the model served as affirmation of the client's current expectations for the system's behavior and as a basis for discussion in cases where the client's expectations of system behavior were not met.

Model Weaknesses. The main weaknesses of the model stem primarily from the inability of the model structure to capture the unique characteristics of the RCW habitat and population at Poinsett Range. Other weaknesses in the model are linked to the relationship between tree density and artificial cavity construction rate.

The basic model was constructed under the assumption that the ecosystem is a homogenous forest area adjacent to other forest areas of similar characteristics. The RCW habitat at Poinsett is actually small and fragmented with a patchwork of wetlands, sandhills, plantation forest, and fire roads. Additionally, the range is relatively isolated from other forest areas. Since the project assumed homogeneous and isolated conditions for the range habitat and "averaged" cavities and clusters over the area, the model fails to address the implications of forest fragmentation and edge effects on the RCW population. Several authors feel that fluctuations in population can occur based on the presence of forest fragmentation or location of clusters in an area on the edge of the habitat (Rudolph and Conner, 1994:365-375; Walters, 1991), but the effects of habitat fragmentation and isolation on the behavior of the RCW are not completely understood. Further study in this area could alter the model given the current model's assumptions which ignore fragmentation and edge effects altogether.

Due to the relatively isolated nature of the Poinsett Range habitat, it is possible that female birds may choose to stay within the ecosystem rather than depart into unsuitable habitat adjacent to the managed area. This isolation also prevents adequate immigration of birds into the managed area. These two major influences may lead to eventual inbreeding and may reduce breeding altogether.

Female RCWs have been known to avoid breeding with closely related males (Walters, 1991). This phenomena can have an enormous impact on the RCW population especially for an isolated habitat such as the Poinsett Range. The limited number of birds reduces the number of unrelated males available for breeding, thereby, severely reducing birth rates for a given population. Such a small population ultimately leads to a reduction in the species gene pool with dubious consequences for the RCW population in the area.

Currently, the effects of such inbreeding is represented by a "relatedness" factor which suggest the female RCW will depart from the ecosystem based on the size of the

RCW population, regardless of how isolated the ecosystem may be from other suitable ecosystems. The mechanisms involved in the female RCWs decision to depart an area or to stay and risk the chances of inbreeding are not well understood. Although the current model attempts to address genetic diversity and incest aversion with the simple mechanism relating total population to relatedness, the model needs a more detailed representation of genetic diversity and its effects in order to completely depict the mechanism responsible for incest aversion.

The second major weakness of the model involves the rate at which cavities are artificially constructed. Although tree density is currently employed in the model to determine cavity goodness and, subsequently, cavity construction, it is based on overall tree density. Cavity goodness does not account for the effects of varying the type of tree controlling cavity goodness; therefore, turkey oak tree density can supplant longleaf pine density and still create favorable conditions for cavity construction. There should be some negative feedback based upon turkey oak density. As turkey oak density increases, the cavity construction should decrease, since an area with heavy turkey oak understory or midstory is unsuitable for cavities and cavities for the RCW are built in longleaf pines only. However, the current model does ensure cavity construction fluctuates with increasing or decreasing tree density itself. The model only fails to address the different types of trees affecting tree density and the implications of varying the mixture of tree density on cavity construction. The cavity construction rate would be more accurately reflected if the rate is based solely on the density of LLP 60 years or older.

VI. Alternative Management Scenarios and Recommendations

The sensitivity of the model to various changes in parameters and influences provided insight into what management practices may be most effective. The client also provided management scenarios for simulation. The following are the scenarios that were run: catastrophic events, including hurricane and pine beetle infestation; management scenarios, which included all existing management practices; no management practices; various tree management scenarios; competitor management; cavity management; artificial translocation of RCWs; and simulation of low genetic diversity represented by low birth rates.

The baseline populations of indicator species shown in Figure 13 (same as Figure 2) represent all current management practices and will be used as a reference in comparing the effects of the various management practices and catastrophic events.

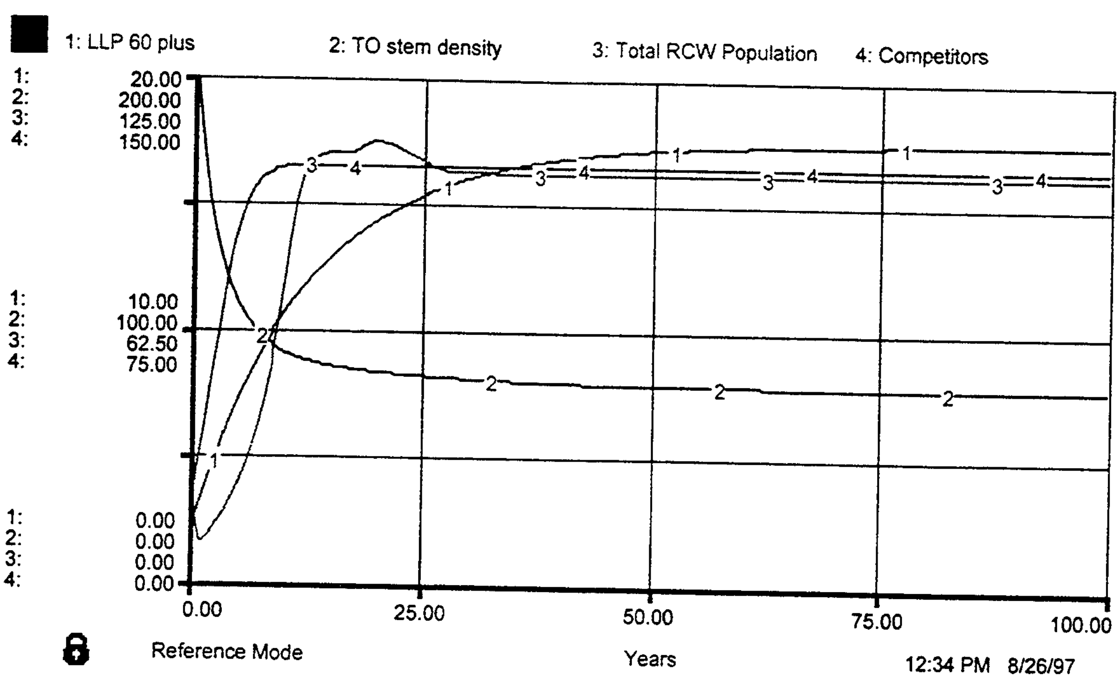

Figure 13. Baseline Populations with Current Management Practices

Catastrophic Events

Longleaf pine ecosystems are subject to periodic catastrophic events such as damaging winds from hurricanes and widespread southern pine beetle infestations. Winds from hurricanes snap older pine trees more than younger pines or turkey oaks due to their height and heartwood fungus. Southern pine beetle infestations are usually triggered by poor tree health. However, when a beetle infestation begins, it will kill both healthy and unhealthy pines of all ages. Beetles can kill large tracts of pine forest and move rapidly.

Hurricane. Figures 14 through 16 show the effects of a hurricane on mature LLPs, turkey oaks, and RCWs. The hurricane was simulated as a pulse to the mortality rates at year 25 with all current management practices in place.

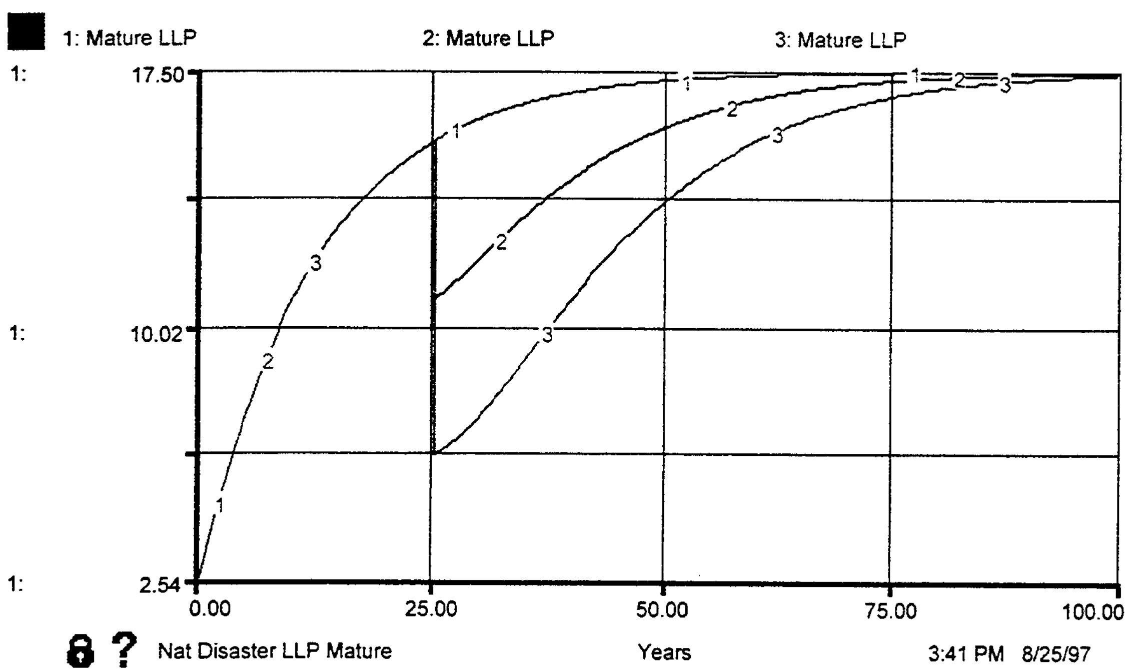

Figure 14. Hurricane Effects on Mature LLP

In Figure 14, trace 1 represents the baseline scenario, trace 2 represents a pulse to the mature LLP mortality of 30% and young LLP of 15%, and trace 3 represents a mature LLP mortality pulse of 60% and young LLP of 30%. These extreme mortality rates are used to simulate what may actually occur in a hurricane. As shown above, the hurricane has a significant impact on the mature LLP population which takes approximately 50 years to recover under current management practices.

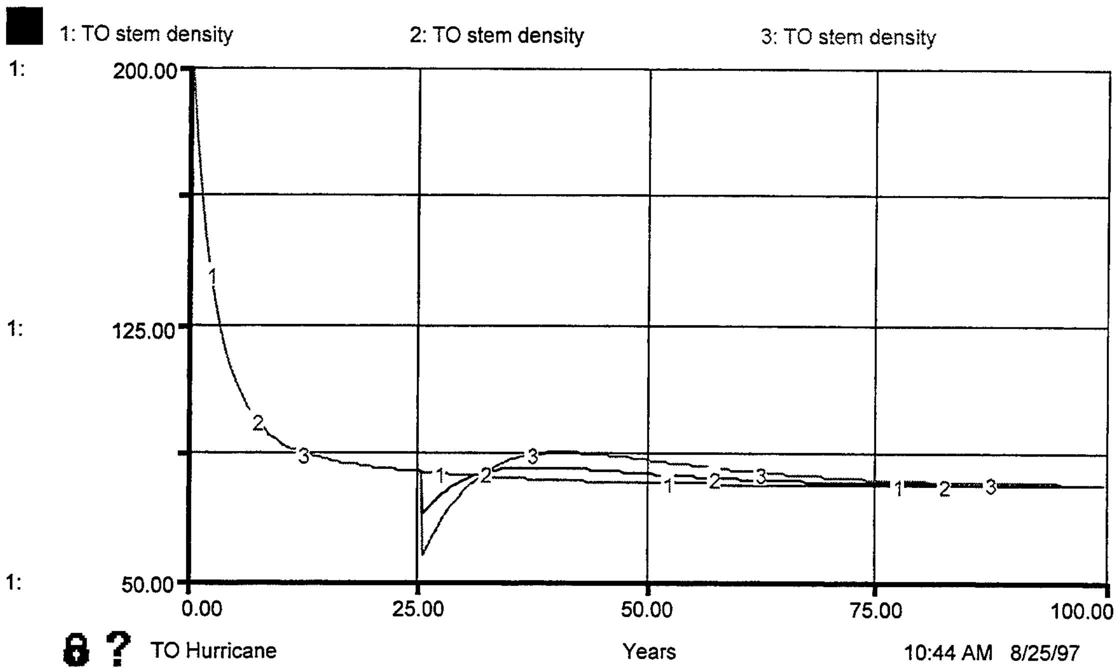

Figure 15. Hurricane Effects on Turkey Oak

In Figure 15, trace 1 represents the baseline scenario, trace 2 represents a pulse to the turkey oak's mortality of 15%, and trace 3 represents a mortality pulse of 30%. These pulses occur simultaneously with pulses to the LLP mortality rates. The hurricane has a much smaller effect on turkey oaks than the mature LLPs because their mortality rate is lower and they can recover faster than the pines. In fact, with the loss of pines, the turkey oaks will actually increase above their steady state level due to decreased competition until they are bought back under control through burning and mechanical removal.

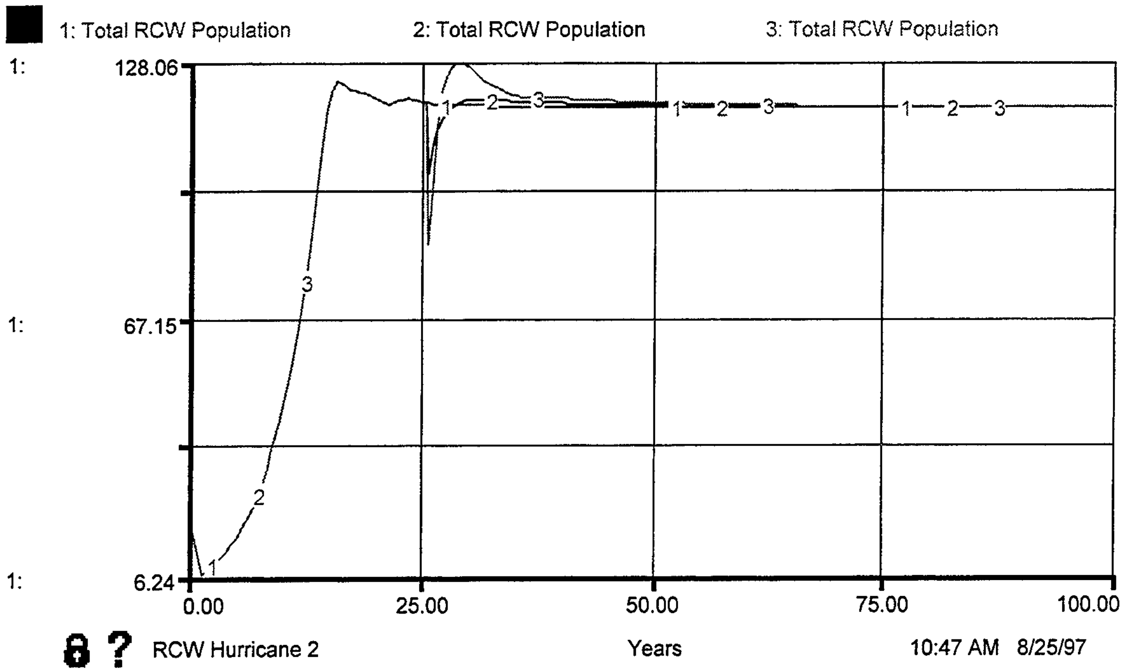

Figure 16. Hurricane Effects on RCW Population

In Figure 16, trace 1 represents the baseline scenario, trace 2 represents a pulse to the RCW mortality of 15%, and trace 3 represents a mortality pulse of 30%. These pulses occur simultaneously with pulses to the LLP and turkey oak mortality rates. The RCWs are initially impacted by the hurricane, but recover very quickly and are fully recovered in about 3 years. This recovery is much faster than we expected and is probably a function of their high birth rate and a poor link between tree density and cavity construction in the model.

Southern Pine Beetle Infestation. Figures 17 and 18 show the effects of a southern pine beetle infestation on mature LLPs and turkey oaks. The beetle infestation was simulated as a pulse to the mortality rates of LLPs at year 25 with all current management practices in place.

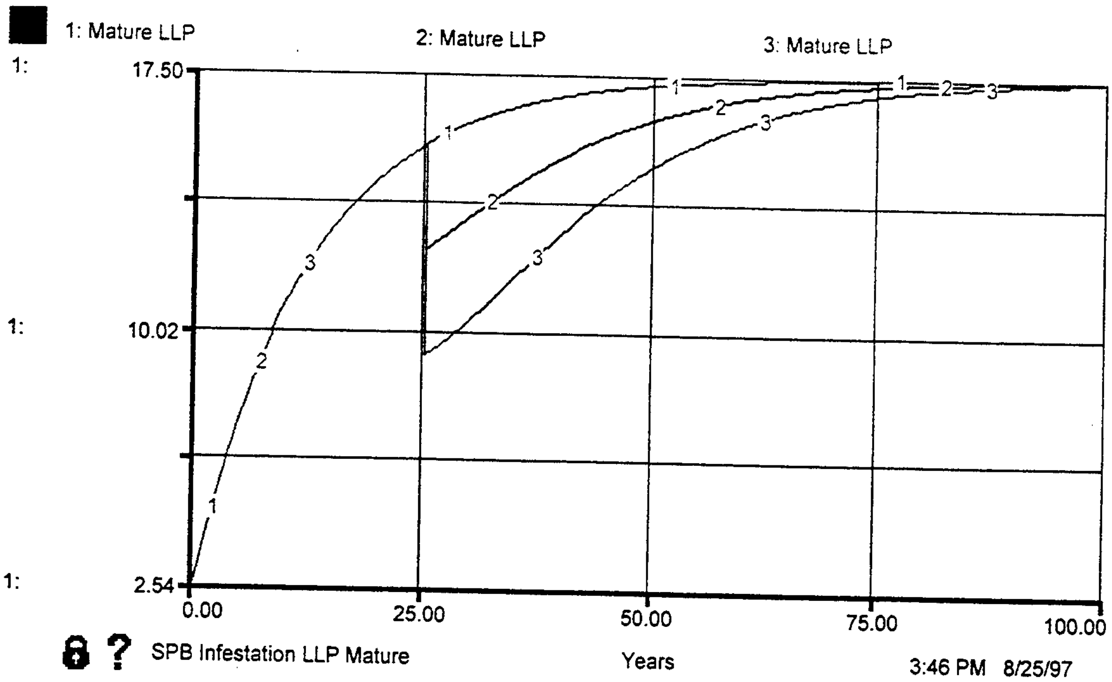

Figure 17. Southern Pine Beetle Effects on Mature LLP

In Figure 17, trace 1 represents the baseline scenario, trace 2 represents a pulse to the LLP mortality of 20%, and trace 3 represents a LLP mortality pulse of 40%. The mortality rates are intended to represent a large tract of LLPs that are destroyed by beetles. As shown above, the beetle effects on the mature LLPs is almost as large as those from the hurricane. Similarly, the LLPs take approximately 50 years to recover.

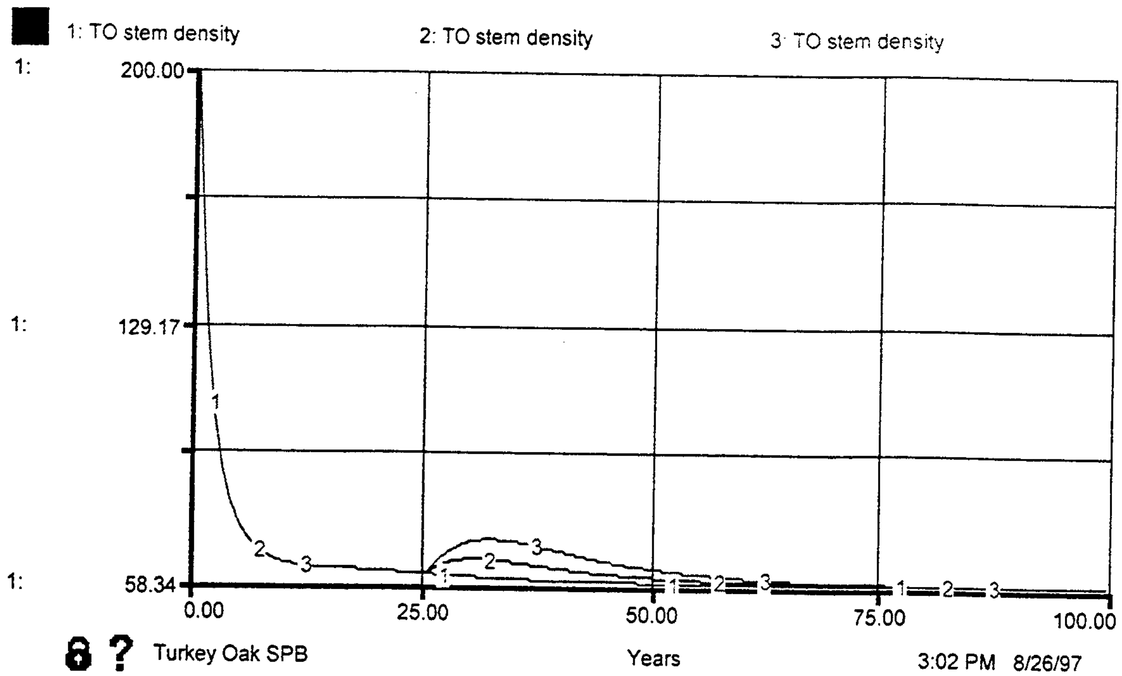

Figure 18. Southern Pine Beetle Infestation Effects on Turkey Oak

In Figure 18, the traces represent the same pulses to LLP mortality rates as in Figure 17. The figure shows that with a loss in LLPs, the turkey oak population will increase above its steady state level due to decreased competition until it is brought back under control through burning and mechanical removal.

Management Scenarios

The client requested several management scenarios be simulated to determine which are most effective in managing the ecosystem in the long-term. The results of these scenarios reflect the assumed mechanisms inherent in the model structure. Each management scenario is tested with all other management practices in place.

<u>All and no current management practices</u>. Figure 13 shows the state of the system with all current management practices in place. Figure 19, below, shows the state of the system with no management practices.

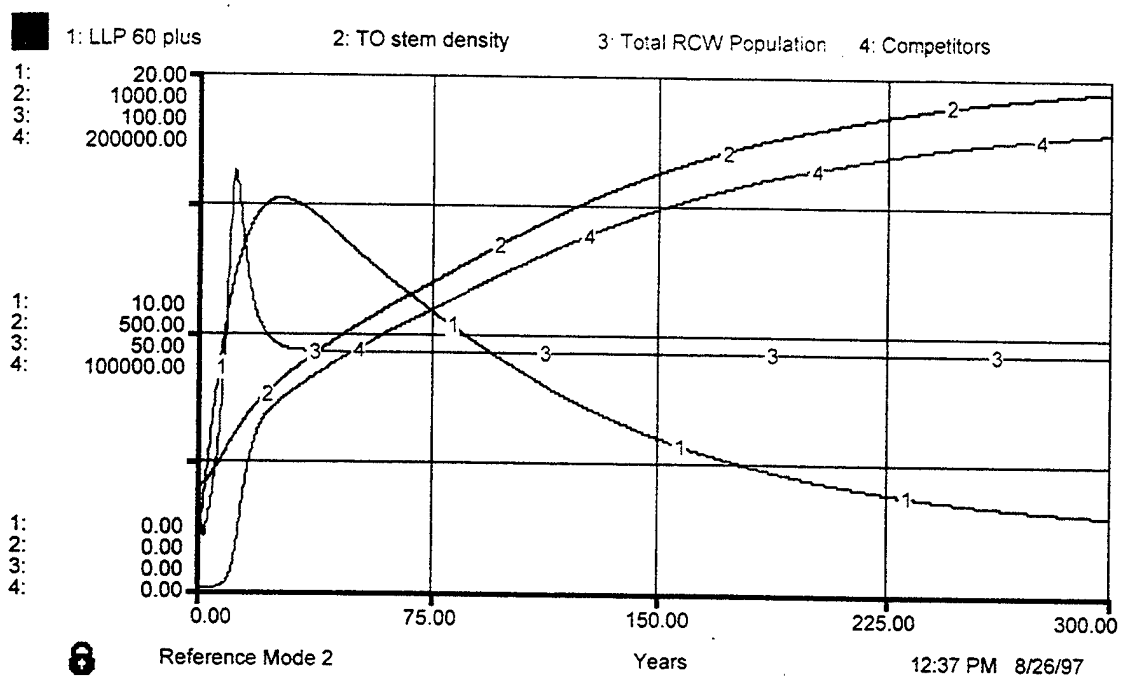

Figure 19. Baseline Populations with No Management Practices

When no management practices are in place and fire is controlled to a wildfire only every 10 years (Figure 19), the system does not reach steady state even after simulating it for 300 years. The trends in both tree populations show that the ecosystem is moving towards its climax successional state which is dominated by turkey oaks. The increasing trend in competitors, which are assumed to be southern flying squirrels in the model, is a product of the increasing number of turkey oaks which provide its primary food source of acorns. The RCW population which peaks and levels off at 50 birds is an anomaly in the system that warrants further investigation. Other scenarios run with combinations of management practices "turned off", especially artificial cavity construction, show that the RCW population will disappear without management. The bottom line is that some management is necessary to maintain the LLP ecosystem.

Tree Management. In this section the effects of tree management practices upon indicator species are examined. These management scenarios include turning mechanical removal rates off and on for both LLPs and turkey oaks with time between burns held constant at the current rate, and varying the time between controlled burns with mechanical removal rates turned on for LLPs and turkey oaks.

Figures 20 and 21 below show the results when mechanical removal is turned on (trace 2), and the results when mechanical removal is turned off (trace 1). With no mechanical removal of LLPs or turkey oaks, the population of turkey oaks increases dramatically, while the population of mature LLPs drops modestly. These simulations only extend to 100 years. In other simulations extending to 300 years (Figure 19), the LLPs decrease and the turkey oaks increase further before finally reaching a steady state. This illustrates that mechanical removal of turkey oaks may play an important role in maintaining populations of both LLPs and turkey oaks near ideal levels when time between burns is maintained at four years.

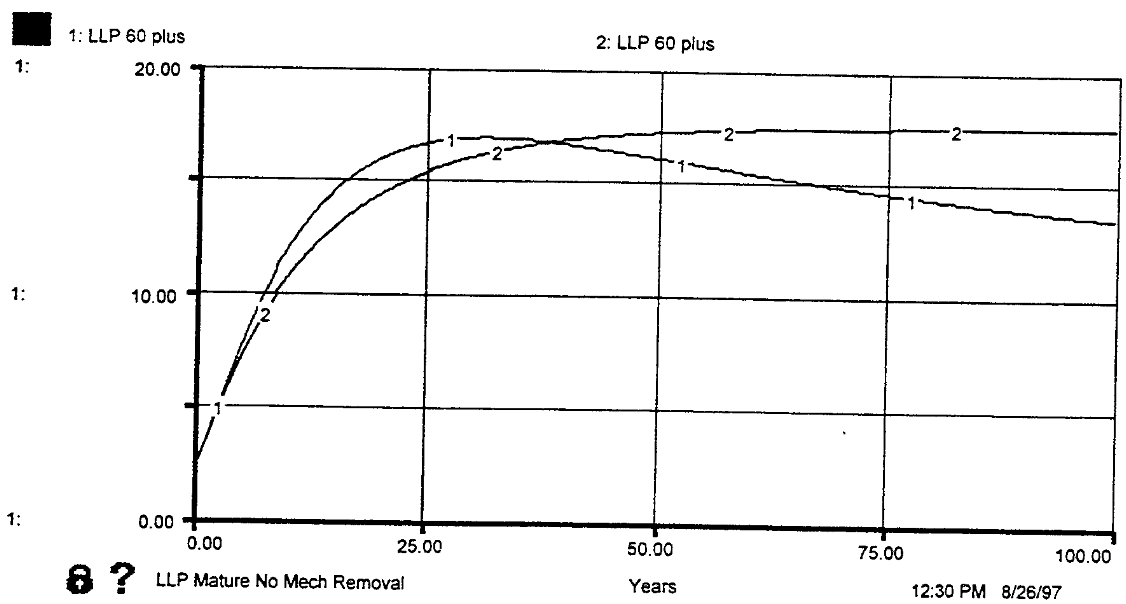

Figure 20. Effects of Mechanical Removal on Mature LLPs

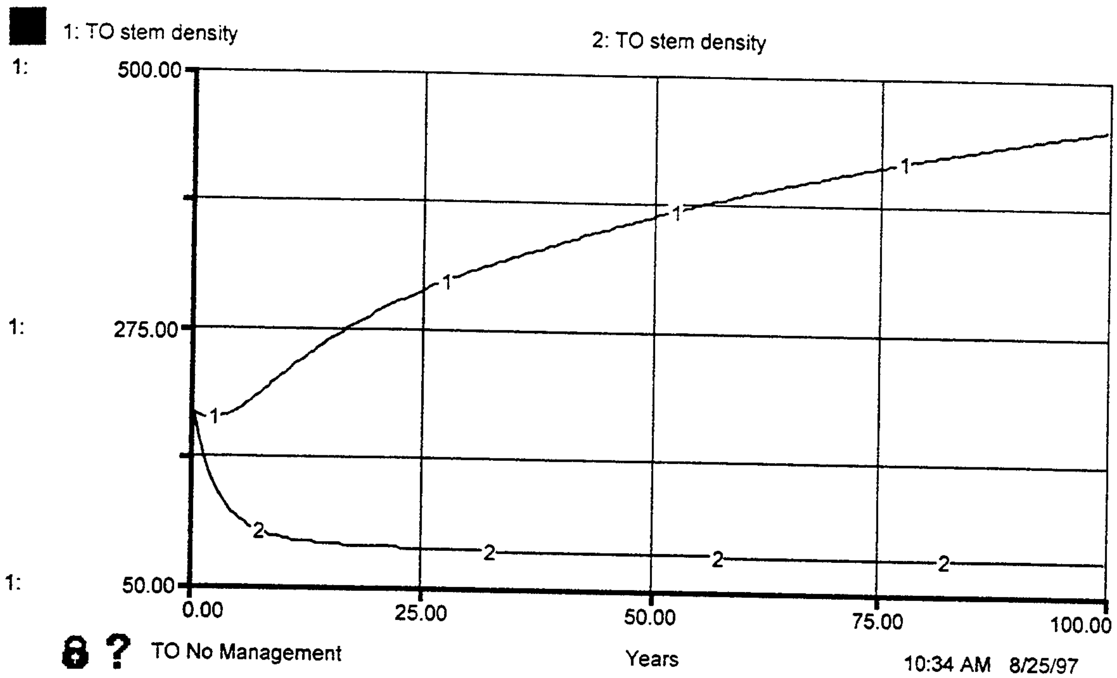

Figure 21. Effects of Mechanical Removal on Turkey Oaks.

With mechanical removal included in the simulation, it was interesting to notice the results when time between controlled burns was varied from 2 to 10 years (traces 1 to 5 respectively in Figures 22 and 23 below). These figures show that as the time between burns decreases, the turkey oak population decreases and the LLP population increases. This is consistent with our intuition and assumptions about the system. Turkey oaks are killed easier by fire, and, once the turkey oak population declines, LLPs increase due to the decreased competition from turkey oaks for resources.

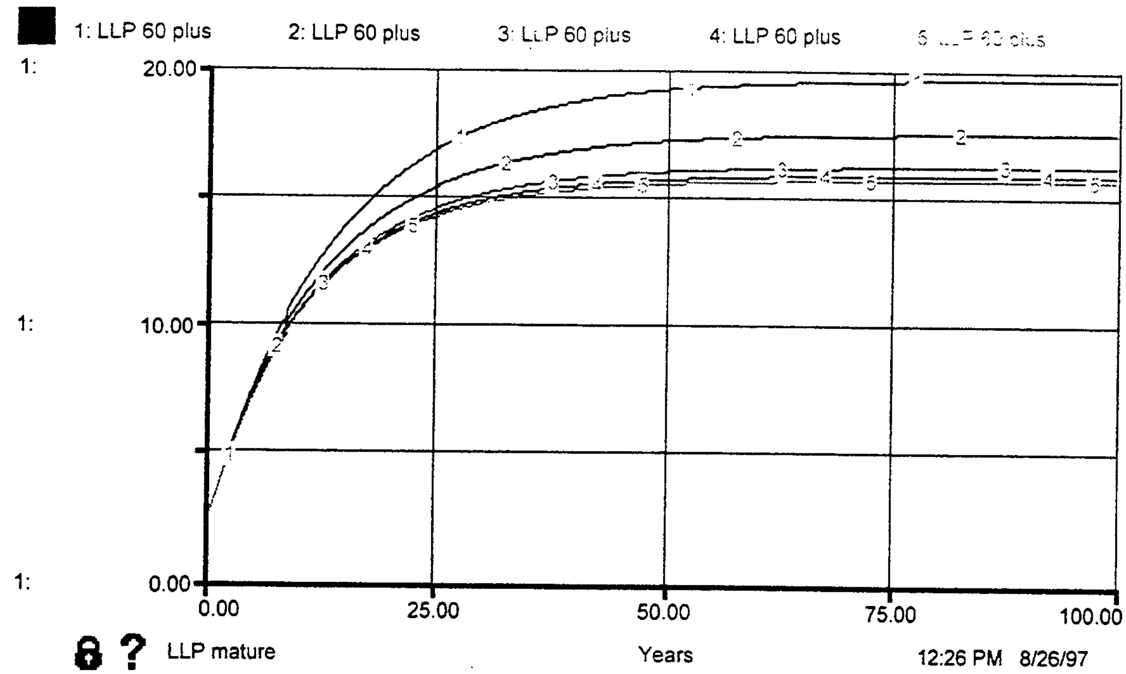

Figure 22. LLP Density with Varying Time Between Burns (2, 4, 6, 8, 10 years)

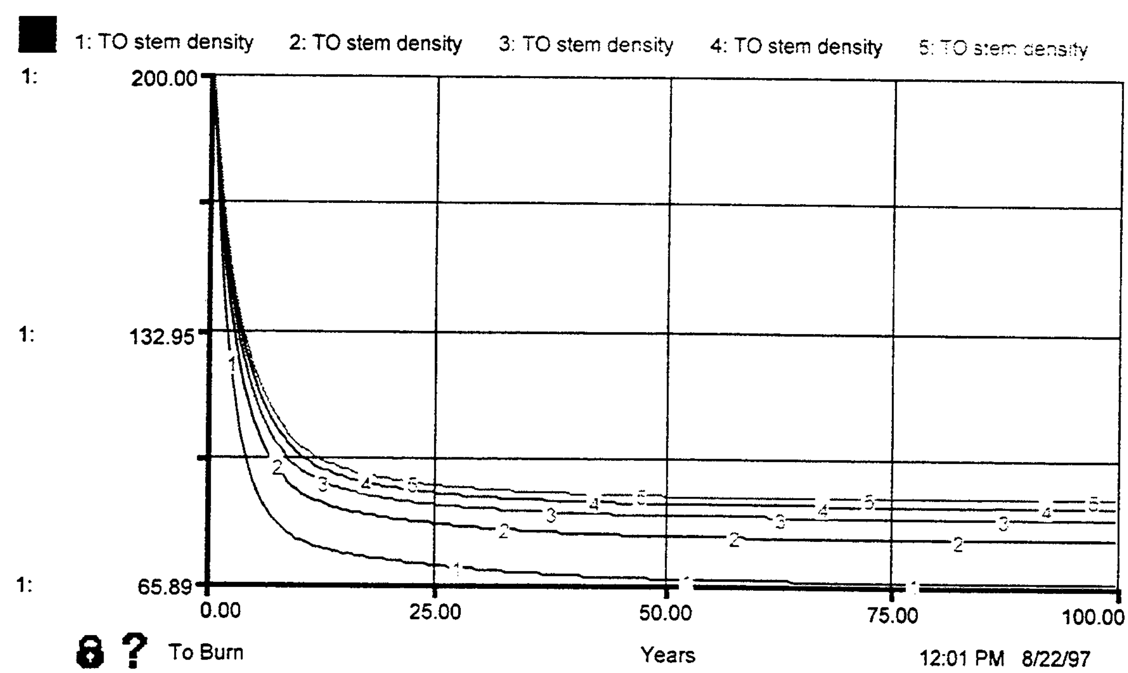

Figure 23. Turkey Oak Density with Varying Time Between Burns (2, 4, 6, 8, 10 years)

One weakness of the model is that the fluctuations that occur in tree populations due to these management practices had almost no effect on RCW population. This should not be the case. A significant decline in mature LLPs should cause a decline in

RCW population. There seems to be a weak link in the model between mature LLP density and the RCW population stemming from the cavity goodness entity. This model weakness was discussed at the end of the previous chapter.

A key insight can be gained from comparing the results of no management (Figure 19), and the results when burn time and mechanical removal are varied. Figure 19 shows that if there is no controlled burning and no mechanical removal, turkey oak densities reach very high levels, dominating the system, while LLPs decrease dramatically, to the point of being nearly wiped out. Comparing this to the mechanical removal results (Figures 20 and 21), where a dramatic increase in turkey oaks can also be seen when mechanical removal is turned off, it is evident that the turkey oak population is largely being controlled by mechanical removal instead of burning. This means that large numbers of turkey oaks must be removed each year to control its population, which may require significant resource expenditures. On the other hand, looking at Figures 22 and 23, the model demonstrates that decreasing the time between burns while mechanical removal is included, the turkey oak population decreases and LLPs increase. In other results that are not reported, by decreasing the time between burns to two years while mechanical removal is not included, the turkey oak population is controlled at levels slightly higher than the baseline. Mature LLPs also reach higher steady state levels than the baseline scenario (Figure 13). These results suggest that decreasing the time between burns may be an effective way to control turkey oaks while maintaining a healthy LLP population. This management practice has the potential to save resources that would otherwise be spent on turkey oak mechanical removal.

Competitor Management. The RCW's primary competitor for roosting and nesting sites is the southern flying squirrel. While other species inhabit RCW cavities, they are too insignificant in their numbers to consider in this model. It was hypothesized that by reducing the number of squirrels, either through promoting increased predation or through active capture, the number of available cavities would increase. This would also result from the reduction of the squirrel's impact upon the RCW which may be promoted by the building of squirrel boxes. Such activity may promote RCW population growth as well as a reduction of required artificial cavity construction efforts (and associated costs). Figure 24 shows how increasing the capture rate of the flying squirrel ultimately impacts the RCW population. *1: Total RCW Population* results from having no capture policy, *2: Total RCW Population* results from the normal capture rate, and *3: Total RCW Population* results from doubling the baseline capture rate.

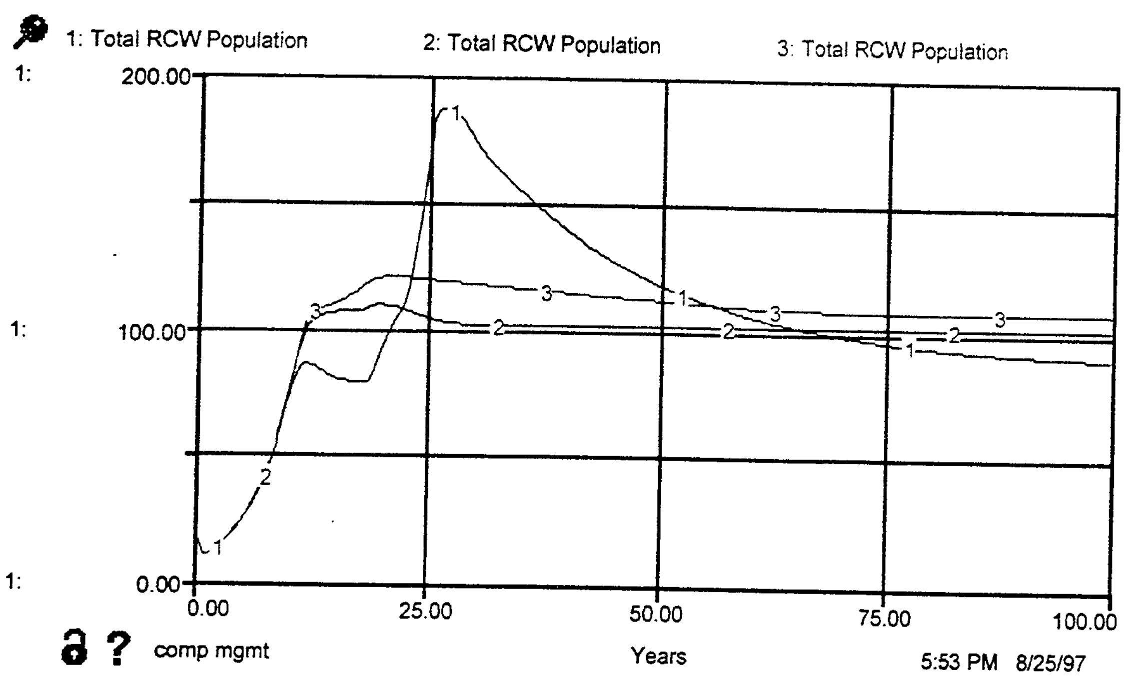

Figure 24. Effects of Competitor Management on RCW Population

This graph shows a contradiction to our initial hypothesis that the RCW would be seriously impacted by the status of the flying squirrel. Having no capture policy shows an initial reduction in RCW population as there are more squirrels competing for RCW cavities and cavity construction is slow to respond to the need for more cavities. As the population of squirrels exhibits overshoot and collapse behavior, brought on by significant reduction in turkey oaks and squirrel overpopulation, the RCW population increases to fill the available cavities and then drops to a reasonable and stable population. Increasing the capture rate, otherwise, has little effect on the size of the RCW population. Maintaining the squirrel population, whether through predation, squirrel box construction, or capture, appears to promote stability for the RCW population; however, in the short run, values from the RCW population are affected very little through manipulation of squirrel population.

Squirrel predator management may be difficult to control. The promoting of a current predator or the introduction of new predators may have severe unknown secondary and tertiary effects upon the environment. If squirrel management practices are implemented, reduction of cavity competition through the use of boxes, and active capturing are the preferred management practices.

Based upon these outputs, the active management of the flying squirrel is not recommended when considering the RCW population alone. Active squirrel management may, however, reduce the efforts required for artificial cavity construction. Costs and other resource allocations could determine which is more effective. We recommend further study of these relationships.

Cavity management. Cavity management entails two essential activities, restrictor plate application due to cavity enlargement by pileated woodpeckers and artificial cavity construction. The application of restrictor plates has a negligible impact on state of the system. The rate of cavity enlargement, as given in the literature and as implemented in the model, is not significant enough to warrant the expenditure of resources to counter such enlargement. Rates of cavity enlargement at the Poinsett Range appear to be greater than the literature values; therefore, further study may be necessary to better ascertain the appropriate rate of cavity enlargement for the Poinsett Range in order to achieve the desired ecosystem state.

Artificial cavity construction is a common management practice used to increase the number of available RCW cavities because the RCW pioneering rate is low and most LLP stands contain immature trees which are difficult for the RCW to pioneer.

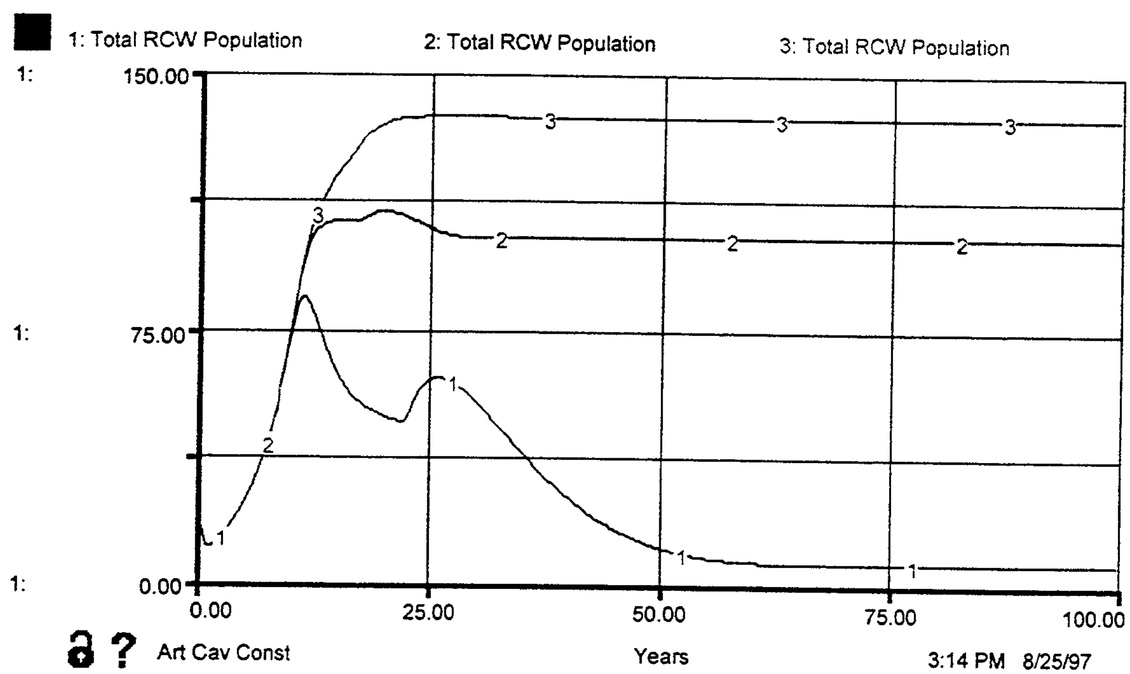

Figure 25. Effect of Artificial Cavity Construction on RCW Population

The plots in Figure 25 represent the RCW population with various artificial cavity construction rates. Trace 1 represents no artificial cavity construction, trace 2 represents the existing rate of construction, and trace 3 represents twice the existing construction rate. Artificial cavity construction plays a major role in establishing a healthy, stable population. As shown above, the more cavities made available through artificial construction, the greater the RCW population.

Studies conducted in the Sand Hills region of North Carolina indicated that artificial cavity construction was an effective method for increasing the number and health of clusters. This has been speculated to increase the population size. (Walters, 1991:516) This is in agreement with the results of our model, that of increasing RCW population due to increasing artificial cavity construction.

With such results, it is our recommendation that artificial cavity construction should be considered a viable management tool. Yet, discussion with the client during the presentation of this model suggests that such results may be counterintuitive. In a cavity-limiting scenario, cavity construction plays a vital role in ensuring roosting and nesting sites. Cavity construction also provides an important buffer to catastrophic events which may reduce the overall number of cavities. However, the population at Poinsett does not appear to expand as a result of increasing available cavities. Other factors such as genetic variability and suitable foraging habitats seem to be far more influential.

Artificial Translocation. The Poinsett Range RCW population is very small resulting in the loss of genetic diversity. Even if the existing population recovers, without adequate immigration these genetic traits can never be regained, making the population less resilient. Artificial translocation is the act of bringing RCWs from another population into the ecosystem to boost the population and improve the genetic diversity.

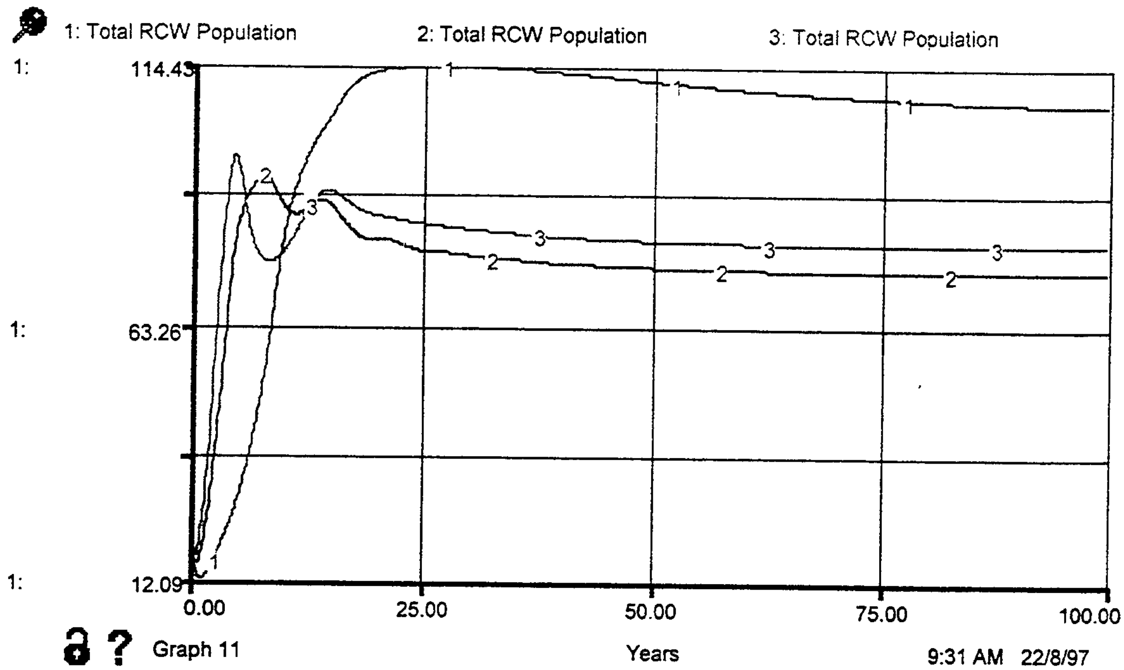

Figure 26. Effect of Translocation on RCW Population

In Figure 26, above, trace 1 represents no translocation, trace 2 represents 5 male and 5 female RCWs imported into the ecosystem each year, and trace 3 represents 10 male and 10 female RCWs imported into the ecosystem each year. Both translocation simulations show a net loss in the RCW population. This result is discussed in detail in the sensitivity section (Chapter 5) dealing with artificial translocation. Artificial translocation is a viable way to improve the population's gene pool, but it must be planned to ensure there is adequate nesting, roosting, and foraging area for the new birds.

Loss of genetic diversity. The client was interested in a simulation of a small RCW population with a limited gene pool in which incest occurs and incest avoidance is possible. Subsequently, it is assumed this scenario is characterized by a population with low birth rates.

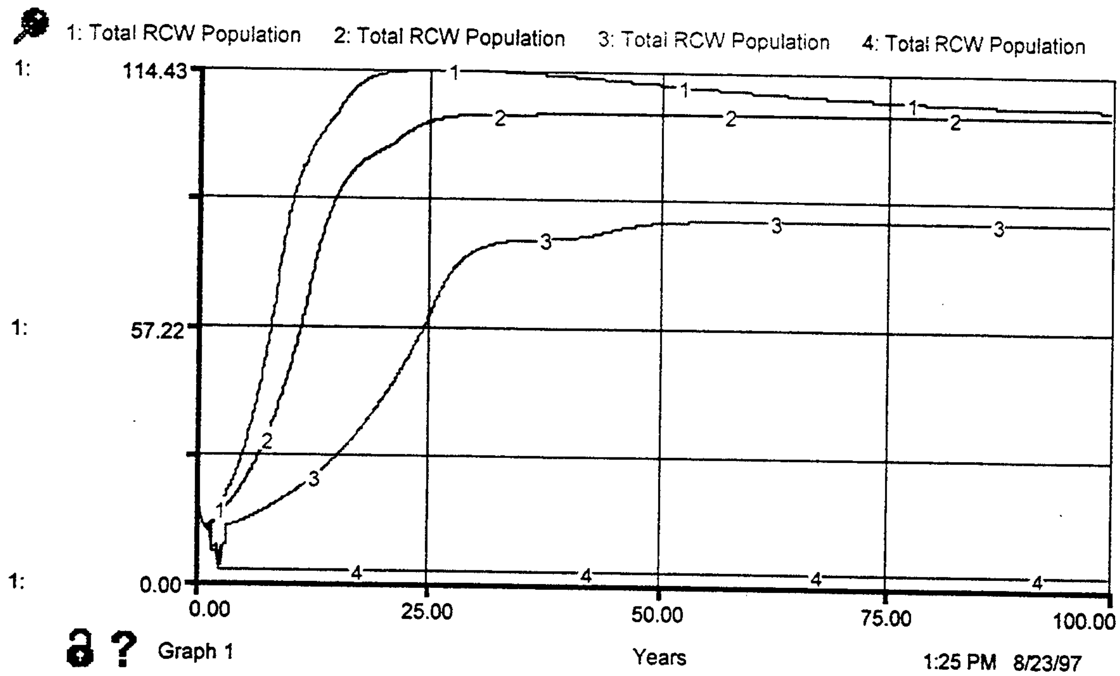

Figure 27. Effects of Birth Rate on RCW Population

In Figure 27, trace 1 represents the RCW population at the baseline birth rate of 1.25, trace 2 represents the population at a birth rate of 1.0, trace 3 represents the population at a birth rate of 0.75, and trace 4 represents the population at a birth rate of 0.5. If birthrates are depressed due to incest and incest avoidance, resulting population levels will be significantly lower or the RCW will be eliminated from the system. This suggests that artificial translocation is an important management practice in preserving small isolated populations.

Recommendations

Our overall recommendation is that an appreciable management effort is required to establish and maintain the desired population of Red-Cockaded Woodpeckers needed to safeguard the primary mission of Shaw Air Force Base and the Poinsett Weapons Range. More specifically, because sustained management of the longleaf pine ecosystem has proven to have the greatest contribution to the RCW habitat, we recommend that active understory management is required to promote this ecosystem including the burning and/or the mechanical removal of turkey oaks. We recommend that increasing burning rate (reducing the time between burning) be implemented. This has the potential to save time and money that would otherwise be spent on turkey oak mechanical removal.

Artificial RCW translocation also appears to be an effective management tool and we recommend that these efforts be sustained. In conjunction with appropriate cavity management, translocation does well to promote genetic diversity thus strengthening the social interactions, reducing emigration caused by incest avoidance behavior, and protects the population from disease.

Artificial cavity construction appeared to be a key element in increasing the RCW population. While current conditions at the Poinsett Range may not support this hypothesis, the literature and the model output do. As a result, we recommend that active construction be considered and that there be further study and modeling of the relationships between LLPs, RCW cavity construction, cluster dynamics, and roosting/nesting behavior.

VII. Conclusions

Research Questions Answered

1. How is the number of RCW clusters affected by environmental factors and management practices? - *It was determined the number of RCW clusters are influenced by the artificial cavity construction rate and the availability of acceptable cavities. Negligible effects were observed from foraging area impacts.*
2. What are the impacts on the longleaf pine ecosystem viability if habitat management is driven by RCW population goals? - *It was determined that the RCW and longleaf pine management goals are not contradictory. Managing to provide an optimum longleaf pine ecosystem provides the RCW with the necessary habitat for foraging and cavity construction.*
3. What management practices will be required to restore and to maintain a longleaf pine ecosystem? - *A combination of mechanical removal and burning yield the more viable longleaf pine ecosystem. Concentrating on decreasing the time between burning will reduce mechanical removal requirements, which may be more cost effective.*
4. How much human resource expenditure with regard to management practices is required to maintain a stable ecosystem? - *The model demonstrated some effort is required to maintain low turkey oak population which ensures an acceptable longleaf pine population. Due to the low pioneering rate of the RCW, management effort will also be required to maintain the appropriate number of acceptable cavities.*

5. What are the effects of management practices on the indicator species? - *The current management practices will decrease the number of turkey oaks, improve longleaf pine age structure, and increase the RCW population.*

Suggestions for Further Study

Although the project model captures a majority of the critical mechanisms of the Poinsett Range ecosystem, several areas which could play a significant role in determining the ecosystem's behavior over time have not been included in the current model or been explored in depth. Some of these areas have already been mentioned as model weaknesses (and should be studied further to address those model weaknesses), so they will not be discussed again. In future efforts to model the Poinsett Range ecosystem, these areas may offer greater insight into the entities and interactions driving the behavior actually seen in the ecosystem and provide a client with a better tool for ecosystem management.

Other Indicator Species. Several different types of species can be utilized to ascertain the health of a particular ecosystem. These indicator species are sensitive to changes occurring in the state of the ecosystem and, consequently, are used to determine the health of the ecosystem. Although the current model contains several indicator species (longleaf pine, turkey oak, squirrels, and RCW), it does not include other species such as wire grass and bobwhite quail which could also be influential in determining the health of the Poinsett Range ecosystem.

Effects of Various Soil Types. Conditions necessary for certain species of trees to thrive were not comprehensively discussed or utilized in constructing the model. The most notable condition which was not pursued is soil condition. Various soil types will significantly impact the level and type of vegetation supported in the ecosystem and, consequently, the heterogeneity of the area and overall diversity of the ecosystem. Soil conditions are especially critical when a particular species such as the longleaf pine is desired. Soil conditions conducive to longleaf pine growth may not support other types of vegetation which play a vital role in the overall range ecosystem. Soil conditions may also limit the choice of strategies available in managing the ecosystem.

Management Strategy Cost Benefit Analysis. Despite numerous types of management practices and their combinations being explored through model simulation to analyze the long-term implications of these practices on the ecosystem, no cost/benefit limitations were placed on the strategies employed. Clearly each of the tested management scenarios has an associated cost. These costs may prove to be the determining factor on which practices could be utilized for managing the Poinsett Range. However, along with the expense of various practices, the benefit received from using a particular strategy should also be weighed to ensure the best management practice is pursued in creating the desired ecosystem state.

The project does not address either of these areas when analyzing long-term simulations for making recommendations about particular management practices. Management scenarios were simulated regardless of the cost involved; however, cost analysis would not alter the management practice's effect on the ecosystem, only the practice selected by the client. Benefits for the ecosystem are derived from the model output for each scenario but are not viewed in conjunction with cost. Costs and the relationship between cost and benefits must be incorporated into future efforts if the client wishes to utilize the model in determining the most effective strategy for managing the Poinsett Range ecosystem given a limited amount of resources.

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Appendix A

Tree Assumptions

General Assumptions:

1. That the LLP population can be divided into 4 age classes: 1 to 30 years, 30 to 60 years, 60 to 95 years, and 95 years and older.
2. The maturation rate for these age classes is assumed to be 1/number of years in age class. For example, in the 1 to 30 year age group, 1/30 of the trees will mature and move to the next higher age class each year.
3. LLP populations are increased only by germination from pine cones. An artificial planting rate can be assumed to be included in this germination rate.
4. That the turkey oak population can be handled as one age category, i.e. it is not necessary to break into various age classes.

Detailed Assumptions:

Model Entity	Assumptions
LLP 1 to 30 years old	1. The LLP from 1 to 30 years old have a dbh of 0 to 20 cm (0 to 8in) with an average dbh of 10 cm (4in). (Platt et al:50 altered by regulation of 60 to 90 BA/acre) 2. LLP from 1 to 30 years old have a mortality rate, a mechanical removal rate (thinning/harvesting), and a maturation rate to older pines. 3. The ideal LLP under 30 years population is assumed to be 150 trees per acre over 8000 acres, or 1,200,000 trees. (Shaw's number combined with regulation of 60 to 90 BA/acre)
LLP 30 to 60 years old	1. The LLP from 30 to 60 years old have a dbh of 20 to 40 cm (8 to 16in) with an average dbh of 30 cm (12in). This age group begins the size of tree needed for good foraging area, but cavity construction is not yet possible in these trees. 2. LLP from 30 to 60 years old have a mortality rate, a mechanical removal rate (thinning/harvesting), and a maturation rate to older pines. 3. The ideal LLP between 30 and 60 years population is assumed to be 20 trees per acre over 8000 acres, or 160,000 trees. (Shaw's number combined with regulation of 60 to 90 BA/acre)

LLP 60 to 95 years old	1. The LLP from 60 to 95 years old have a dbh of 40to50 cm (16 to 20in) with an average dbh of 45cm (18in). These trees are also good for foraging habitat. Artificial cavities can now begin to be inserted into these trees. 2. LLP from 60 to 95 years old have a mortality rate, a mechanical removal rate (thinning/harvesting), and a maturation rate to older pines. 3. The ideal LLP between 60 and 95 years population is assumed to be 15 trees per acre over 8000 acres, or 120,000 trees. (Shaw's number combined with regulation of 60 to 90 BA/acre)
LLP 95 years and older	1. The LLP over 95 years have a dbh over 50 cm (20in) with an average dbh of 56cm (22in). These trees are also good for foraging habitat. Artificial and natural cavities can now begin to be inserted into these trees. 2. LLP over 95 years are limited only by their mortality rate and a mechanical removal rate (thinning/harvesting). 3. The ideal LLP over 95 years population is assumed to be 10 trees per acre over 8000 acres, or 80,000 trees. (Shaw's number combined with regulation of 60 to 90 BA/acre)
Turkey Oaks	1. The turkey oak stock includes turkey oaks of all ages, with an average dbh of 4 in. 2. The ideal turkey oak population is assumed to be 50 trees per acre over 8000 acres, or 400,000 trees. (Shaw's number combined with regulation of 60 to 90 BA/acre) 3. Turkey oaks have a germination rate, a mortality rate, and a mechanical removal rate.
LLP Germination	The LLP germination rate is a function of the total number of LLPs, and the total shading, which is a function of total number of trees per acre. With a shading of 0 (full sun) the germination rate will .597 new trees for each current tree, with a shading of .5 a germination rate of .501, and with a shading of 1 (complete shade), a germination rate of 0. Germination rates are higher when more sun is available. (graph)
Turkey oak germination	Turkey oak germination is a function of the total number of live turkey oaks and total shading, which is a function of total number of trees per acre. A shading of 0 gives a germination rate of .15 new turkey oak per live turkey oak, a shading of .5 giving a germination rate of .121, and a shading of 1 giving a germination rate of .0075. Germination rates of turkey oaks are assumed to be not as drastically affected by shading as are LLPs. (graph)

Turkey Oak Resprout	It is assumed that 67% of the turkey oaks that die as a result of burning will resprout.
Shading	Shading by living trees is assumed to affect the successful germination of both LLPs and turkey oaks. This is a factor that varies form 0 to 1 based upon the density of turkey oaks and of LLPs, with turkey oaks having the greater impact on shading (maximum value of .7), while the LLPs have less of an impact (maximum value of .3).
LLP Shading	LLP shading is a function of LLP density with 0 trees per acre having a shading of .0015 and 300 trees per acre having a shading of .3. LLP density is the sum of all LLPs (all ages) divided by the total area. (graph)
Turkey Oak Shading	Turkey oak shading is a function of turkey oak density with 0 trees per acre having a shading of .0 and 1000 trees per acre having a shading of .7. (graph)
LLP Natural Mortality Rate	Natural mortality varies inversely with total tree health and is different for the four age groups of LLP. Baseline intrinsic mortality rates came from Platt et al (500.), and were used in determining the dynamic death rates. (graph)
LLP 1 to 30 Natural Mortality	For LLP less than 30 years, when tree health is .2, the natural mortality is .099 while when the tree health is 1 the natural mortality is .01.
LLP 30 to60 Natural Mortality	For LLP between 30 and 60 years, when tree health is 0, the natural mortality is .01 while when the tree health is 1 the natural mortality is .001.
LLP 60 to 95 Natural Mortality	For LLP between 60 and 95 years, when tree health is 0, the natural mortality is .00995 while when the tree health is 1 the natural mortality is .001.
LLP 95+ Natural Mortality	For LLP greater than 95 years, when tree health is 0, the natural mortality is .0496 while when the tree health is 1 the natural mortality is .00545.
Turkey Oak Natural Mortality	For the turkey oaks, assuming the average age is 40 years, the natural mortality varies with total basal area per acre, with a density maximized at 150 having a mortality rate of .0498 and a density of 0 having a mortality rate of 0.

LLP Tree Health - general	Tree health varies with the burn health, the mechanical removal health, and the basal area health, weighted .1, .3, and .6, respectively.
Burn Health	The burn health for each tree group is a function of the burn time, with a burn time of 4 years giving a maximum burn health, and the burn health decreasing if the burn time increases or decreases. The burn time is set at a constant value of 4 years, but can be altered to explore different management practices. The values are similar for each group of trees.
Mechanical Removal Health	The mechanical removal health is a function of the removal rate per area for each group of trees. The removal rate is the excess trees divided by the time between thinning, which is set at 8 years for the LLPs and 4 years for the turkey oaks. The excess trees are the difference between the ideal stem density and the actual stem density. Note that if the ideal is greater than the actual, then no mechanical removal will occur.
Mechanical Removal of Trees	The mechanical removal rate for LLP represent thinning for pulpwood, while for the turkey oaks it represents clearing all hardwoods in the area. We assume the trees with weaker health will be removed, and any removal will increase the health of the entire stand.
LLP 1 to 30 Mech. Rem. Health	For the LLP less than 30 years, a mechanical removal rate of 0 has a mechanical removal health of .005 while a mechanical removal rate of 5 has a mechanical removal health of 1. (graph)
LLP 30 to 60 Mech. Rem. Health	For the LLP between 30 and 60 years, a mechanical removal rate of 0 has a mechanical removal health of .015 while a mechanical removal rate of 1 has a mechanical removal health of 1. (graph)
LLP 60 to 95 Mech. Rem. Health	For the LLP between 60 and 95 years, a mechanical removal rate of 0 has a mechanical removal health of .01 while a mechanical removal rate of .5 has a mechanical removal health of 1. (graph)
LLP 95+ Mech. Rem. Health	For the LLP greater than 95 years, a mechanical removal rate of 0 has a mechanical removal health of .005 while a mechanical removal rate of 1 has a mechanical removal health of .995. (graph)

Mechanical Removal Turkey Oaks	For the turkey oaks, removal will occur when the excess tress are greater than 0 and will occur at a rate of the excess turkey oaks divided by the turkey oak thinning time, which is set at 4 years.
Basal Area Health	The basal area health for each age group is a function of the total basal area per acre.
LLP 1 to 30 BA Health	For the LLP less than 30 years, a basal area of 0 has a tree health of 1 while a basal area of 180 has a tree health of 0. At a basal area of 90 the tree health will be .835. (graph)
LLP 30 to 60 BA Health	For the LLP between 30 and 60 years, a basal area of 0 has a tree health of 1 while a basal area of 180 has a tree health of 0. At a basal area of 90 the tree health will be .85. (graph)
LLP 60 to 95 BA Health	For the LLP between 60 and 95 years, a basal area of 0 has a tree health of 1 while a basal area of 180 has a tree health of 0. At a basal area of 90 the tree health will be .795. (graph)
LLP 95+ BA Health	For the LLP greater than 95 years, a basal area of 0 has a tree health of 1 while a basal area of 180 has a tree health of 0. At a basal area of 90 the tree health will be .835. (graph)
Burning	The percentage of trees in each age group that die directly from burning is a function of the fire intensity, with the LLPs resisting fire more as their age increases. The turkey oaks burn more as the fire intensity increases.
Fire Intensity	The fire intensity is a function of the level of fuel and the stem density fire factor, each weighted equally. If there has been fire management in the past, then the intensity will never exceed .75, otherwise it can vary from 1 (large amount of fuel and a thick forest), to 0 (no fuel and an ideal density.)
Fuel	The level of fuel is a function of the fuel from the turkey oaks and fuel from the LLPs (multiplied by the time between burns), weighted .33 and .66, respectively. The time between burns is a function of the burn time (set at 4 years) with a burn time of 0 having a time between burns of .005 and a burn time of 10 having a time between burns of 1. We have a time between burns of .69.

LLP Fuel	LLP fuel level is a function of the LLP basal area, where basal area is the stem count per acre times the average radius squared times pi. The fuel level varies from 0 to 1 as the basal area varies from 0 to 150. (graph)
Turkey Oak Fuel	Turkey oak fuel level is a function of the turkey oak basal area, where basal area is the stem count per acre times the average radius squared times pi. The fuel level varies from 0 to .985 as the basal area varies from 0 to 10. (graph)
Stem Density Fire Factor	The stem density fire factor is a function of the stem density fire factors of the four LLP groups multiplied by their respective burn weights, which are .5 for the 1 to 30 group, .3 for the 30 to 60 group, and .2 for 60 to 95 group and the 95+ group combined. Each stock stem density fire factor is a function of the stem density of the four LLP groups per acre.
Stem Density Fire Factor - LLP 1 to 30 years	For the LLP between 1 and 30 years, a stem density of 0 gives a stem density fire factor of 0, a stem density of 150 gives a stem density fire factor of .41, and a stem density of 300 gives a stem density fire factor of 1.
Stem Density Fire Factor - LLP 30 to 60 years	For the LLP between 30 and 60 years, a stem density of 0 gives a stem density fire factor of .005, a stem density of 40 gives a stem density fire factor of .47, and a stem density of 80 gives a stem density fire factor of 1.
Stem Density Fire Factor - LLP 60 + years	For the LLP greater than 60 years, a stem density of 0 gives a stem density fire factor of 0, a stem density of 25 gives a stem density fire factor of .455, and a stem density of 50 gives a stem density fire factor of 1.
% Deaths per burn - LLP 1 to 30 years	For the LLP between 1 and 30 years, at a fire intensity of 1 we will see 99.5% trees dying due to burning, at a fire intensity of .5 we will see 14.5% trees dying, and at a fire intensity of 0 we will see 0% trees dying. (graph) (Numbers come from Shaw AFB)
% Deaths per burn - LLP 30 to 60 years	For the LLP between 30 and 60 years, at a fire intensity of 1 we will see 80.5% trees dying due to burning, at a fire intensity of .5 we will see 9% trees dying, and at a fire intensity of 0 we will see 0% trees dying. (graph) (Numbers come from Shaw AFB)
% Deaths per burn - LLP 60 to 95 years	For the LLP between 60 and 95 years, at a fire intensity of 1 we will see 50% trees dying due to burning, at a fire intensity of .5 we will see 4.75% trees dying, and at a fire intensity of 0 we will see 0% trees dying. (graph) (Numbers come from Shaw AFB)

% Deaths per burn - LLP 95 and older	For the LLP greater than 95 years, at a fire intensity of 1 we will see 29.9% trees dying due to burning, at a fire intensity of .5 we will see 5.5% trees dying, and at a fire intensity of 0 we will see 0% trees dying. (graph) (Numbers come from Shaw AFB)
% Deaths per burn - Turkey oaks	For turkey oaks, at a fire intensity of 1 we will see 90% trees dying due to burning, at a fire intensity of .5 we will see 25.5% trees dying, and at a fire intensity of 0 we will see 0% trees dying. (graph) (Numbers come from Shaw AFB)
Ips Beetle Infestation	Ips beetle infestation is a function of total tree health for each group of LLPs. When the total health varies from .2 to 1, the Ips beetle infestation factor varies from .02 to .002. Beetle infestation rates are assumed to be the same for each tree age category. (Graphs)
Southern Pine Beetle Infestation	The southern pine beetle infestation is a function of total tree health for each group of LLPs. When total health is 0, the infestation rate is .905. The rate drops off until it reaches 0 when total health equals .4. The rate remains at 0 while the total health varies from .4 to 1. Beetle infestation rates are assumed to be the same for each tree age category. (Graphs)

Cavity Assumptions

General Assumptions:

1. The number of acceptable available cavities (Acpt Avail Cav) is the primary unit of interest.
2. The flow into the Acpt Avail Cav node has inflow of cavity construction (Cavity Const Rate), an outflow of cavity tree loss, and biflows of RCW occupied cavities (RCW Cav Ocp), Squirrel occupied cavities (Squir Cav Ocp), and cavities made unacceptable through enlargement (Unacpt Cavity).
3. Total number of cavities consists of Total Cav = Acpt Avail Cav + RCW Cav Ocp + Squir Cav Ocp + Unacpt Cavity.
4. When a cavity dies, its occupant automatically fills another available cavity.

Detailed Assumptions:

Model Entity	Assumptions
Acpt Avail Cav	This stock increases with cavity construction and as cavities are given up by occupants. It decreases as cavities are occupied or enlarged.

Art Cavity Rate	The maximum rate is 20 per year. The rate is a function of existing available cavities. As available cavities decrease the artificial cavity rate increases.
Pioneering Rate	The maximum rate is 3 per year. The rate is a function of existing available cavities. As available cavities decrease the pioneering rate increases.
LLP Find Rate	This conceptualizes the chance of a RCW finding an acceptable tree to pioneer. If there are many, the chances are good, if there are few, the chances are slim.
Total Cav	This is an aggregate of acceptable and unacceptable cavity trees
Cavity Tree Loss	1. This is the loss of cavity trees via an increased mortality due to the weakening of the infrastructure as a result of cavities. It is inclusive of RCW, squirrel, and acceptable cavity loss. 2. A "resident" occupies another cavity if the tree dies. Cavities will be reoccupied unless made unacceptable.
RCW Ocp Rate (biflow)	This is equivalent to RCW pop change.
Squir Ocp Rate (biflow)	This is equivalent to the squirrel competition pressure value.
Competition Pressure	(Birth - death - capture) * fraction - squirrel box rate. Squirrel population change times fraction living in cavities less the number of squirrels boxes installed each year yields change in cavity occupancy per year.
Frac N Cav	Fraction of squirrels that occupy RCW cavities = 0.67.
Competition Birth Rate	According to (Sawyer:1985) squirrels have two litters per year of about 2.5 squirrels per litter. Therefore, each breeding pair would produce 5 squirrels per year and each squirrel would produce 2.5 squirrels per year. Since all squirrels are not of breeding age we assume a birth rate of 2 squirrels per squirrel per year.
Food Factor	A limiting factor on squirrel birth rate which is a function of turkey oak density. Turkey oaks provide acorns which is squirrel primary food source.
TO Basal-area	Uses turkey oak density to determine optimum foraging conditions (Food per Squirrel) and protection via cover (Predation Rate)
Capture\mort_rate	This is a combination of natural mortality rate and the management practice of capturing squirrels.

Unacpt Cavity	Cavities enlarged by pileated woodpeckers.
Opening Enlarge	Cavity enlargement rate less application of restricting plates.
Enlargement Rate	0.032 -- trees/year (Connor & others 1991:535) are enlarged by pileated woodpeckers.
Opening Plates	Rate of restrictor plate installation reduces the number of unacceptable cavities and reduces the enlargement rate by making cavities less available for enlargement.
Unacpt Cav Mort	Use cavity tree mort rate
Acc Nat Cav Trees	Acceptable trees for pioneering = Cav goodness * LLP 95 plus.
Cav_goodness	Somewhat normal curve vs density (Total Basal area/Area) between 0 to 140 Sqft/acre. This assigns a value between 0 and 1 based on total tree density. If density is between 60 and 80 sqft/acre, then cavity goodness =1.
Acc Art Cav Trees	Acceptable trees for artificial cavity construction = Cav goodness * Tot over 60
Tot over 60	All trees over 60 -- LLP 95 plus + LLP 60 to 95
Cav Const Rate	Maximum artificial cavity construction rate per year in every tree possible. Takes the minimum of holeless trees or number of construction cavities by pioneering and artificial construction cavities. -- Essentially, one can't have more cavities than you have cavity trees.
Cav Mort Rate	LLP 60 plus Mort Rate + Delta Mort Rate This is the mortality rate of mature LLP trees as determined by the tree model plus the increase in mortality due to there being a cavity in the tree.
Delta Mort Rate	This is the difference between the mortality rate of LLP in the literature and that of cavity trees in the literature. This gives us a good indication of the observational increase in mortality due to presence of a cavity. As a result, whatever the mortality found in the tree model, that mortality will be represented in the cavity model.
Lit Cav Mort Rate	Rate of cavity tree mortality found in the literature = .013 Deaths/Tree/Year (Connor & Others, 1991).

Lit Tree Mort Rate	Death rate of two stocks of not-cavity trees weighted by their population = (LLP 95 plus * 0.138 + LLP 60 to 95 * 0.075) / Tot over 60

RCW Assumptions

General Assumptions:

1. The primary influences which contribute to the increase of the number of RCWs are the number of breeding pairs, number of helpers per active cluster, and foraging area.
2. The primary influences which decrease the number of RCW are natural mortality, predation, and RCW departure from the managed area.
3. The extent the RCW population will flourish is largely dependent on the availability of suitable cavities per cluster.
4. If an RCW has no mate, nor an available cavity, the RCW will leave the managed area.

Detailed Assumptions:

Model Entity	Assumptions
1. Female Fledgling 2. F One Year Old 3. F Two Year Old 4. F Three Year Old 5. F Four Year Old 6. F Five Year Old 7. F Six Year Old	1. Stocks representing the number of female birds in each year in the life of typical lifespan of a female RCW. 2. The average life span of a female RCW is 6 years.
1. Male Fledgling 2. M One Year Old 3. M Two Year Old 4. M Three Year Old 5. M Four Year Old 6. M Five Year Old 7. M Six Year Old	1. Stocks representing the number of male birds in each year in the life of typical lifespan of a male RCW. 2. The average life span of a male RCW is 6 years.
1. F Birth 2. M Birth	The number of female and male births are the same.
Breeding pairs	1. Breeding pairs are a function of the number of males and females and the availability of cavities per cluster. 2. Only one breeding pair will occupy a cluster. 3. A cluster requires two cavities in order to house a breeding pair.

1. F Birth Rate per Breeding Pair 2. M Birth Rate per Breeding Pair	1. The birth rate for males and females are the same 2. Influenced by the foraging area; a minimum foraging area is necessary to produce the nutritional requirements to produce a normal number of eggs.
Helper per Cluster w\ B	1. Function of the number of potential helpers per Cluster w\ BP and the potential number of clusters with a breeding pair. If there is an excess of cavities per cluster, the number of helpers per active cluster is the same as the number of potential helpers per active cluster. Otherwise, the number of males in excess of the number of cavities is assumed to depart the managed area. 2. This entity will influence the survivability of the fledglings. Thus the number of helpers per cluster will affect the mortality rate of the fledglings.
1. Foraging Area Factor 2. Foraging Area Factor 2 (Foraging Area Factor con't)	1. A minimum area of foraging area is required to produce the "normal" amount of fledgling per breeding pair. If the available foraging area exceeds this amount, the birth rate is not effected; if the foraging area is less than the minimum required, the production rate of each breeding pair is assumed to diminish. 2. The foraging area will also influence the departure rate of the RCW from an area of management concern. Poor forging area will enhance the departure rate of breeding age males and females from the area of management concern. Adequate foraging area will not necessarily prevent birds from departing; RCWs will just depart at the typical rate.
1. FF Mortality Rate 2. One Mortality Rate 3. Two Mortality Rate 4. Three Mortality Rate 5. Four Mortality Rate 6. Five Mortality Rate 7. F Mortality Rate	Predation, disease, strafing deaths, etc, is included in the mortality rate
1. MF Mortality Rate 2. M One Mortality Rate 3. M Two Mortality Rate 4. M Three Mortality Rate 5. M Four Mortality Rate 6. M Five Mortality Rate 7. M Mortality Rate	Predation, disease, strafing deaths, etc., is included in the mortality rate.

1. FF Mortality 2. One Mortality 3. Two Mortality 4. Three Mortality 5. Four Mortality 6. Five Mortality 7. F Mortality	Predation is included within the mortality of each group of RCWs of a particular age.
1. MF Mortality 2. M One Mortality 3. M Two Mortality 4. M Three Mortality 5. M Four Mortality 6. M Five Mortality 7. M Mortality	Predation is included within the mortality of each group of RCWs of a particular age.
1. Departing females 2. Departing males (Departing males/females con't)	1. The number of females departing will be evenly distributed over the entire portion of the female population that is of breeding age. 2. The number of males departing will be evenly distributed over the entire portion of the male population that is of breeding age. 3. Female RCWs will depart the managed area if first, it can not find a mate and secondly, if there are not enough clusters available for a new breeding pair. 4. Male RCW will depart if not enough suitable cavities per cluster exist. 5. The relatedness index and the foraging area factor will influence the rate of departing males and females. As the relatedness index increases, the number of females departing will increase. As the foraging area decreases, the number of departing males and females will increase.
1. FF to One 2. One to Two 3. Two to Three 4. Three to Four 5. Four to Five 6. Five to Six	Entities defining the progression of female RCWs through each age group until natural death.
1. MF to One 2. M One to Two 3. M Two to Three 4. M Three to Four 5. M Four to Five 6. M Five to Six	Entities defining the progression of male RCWs through each age group until natural death.
Life Span Factor	Defines the progression of RCWs through each life stage.

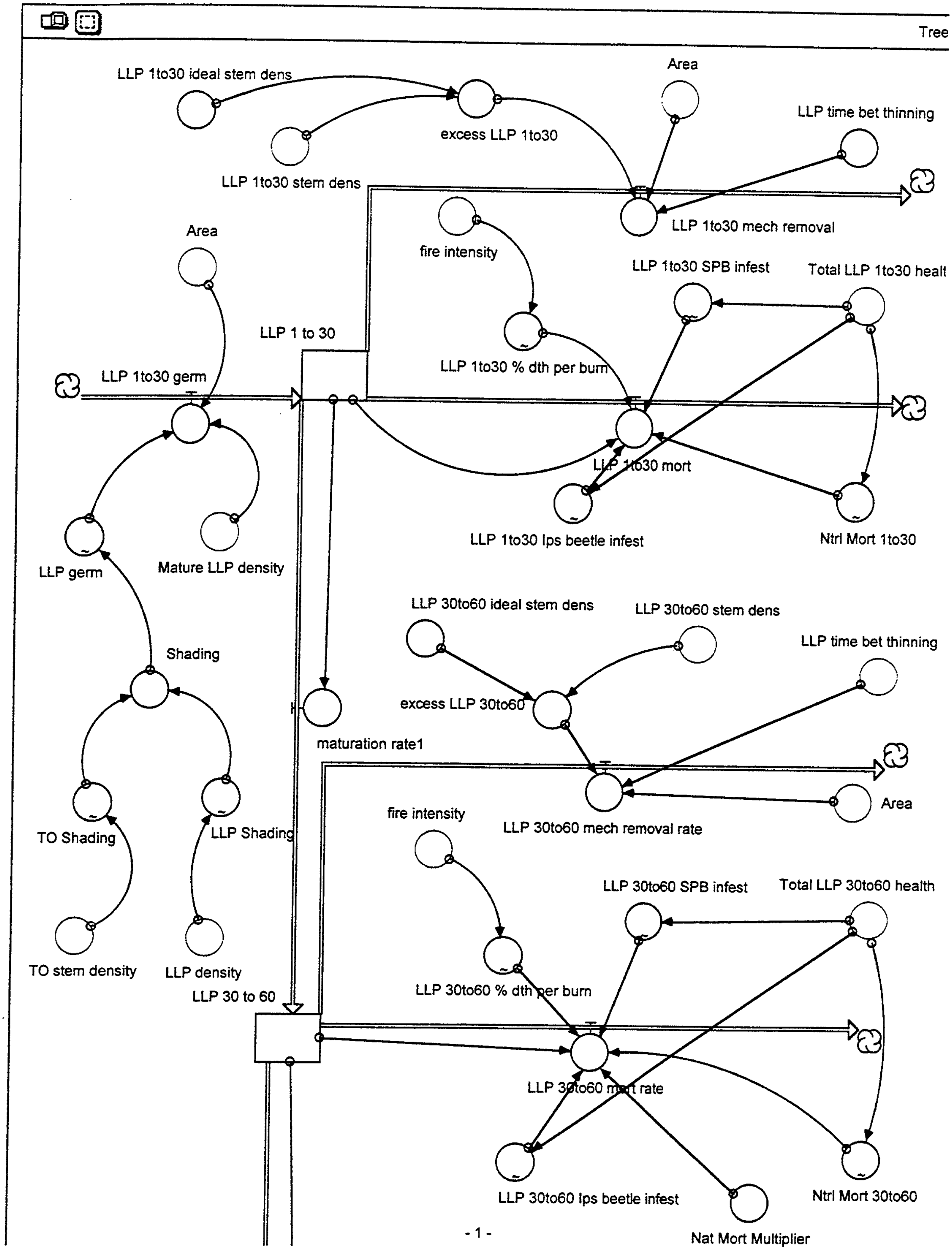
1. Males of Breeding Age 2. Females of Breeding Age	1. Defined as the number of males and females, respectively, older than one year. 2. RCWs older than one year are potential breeders.
1. Total Males 2. Total Females	Total males and total females are the total number of males or females of breeding age in addition to the number of male or female fledglings, respectively.
Total RCW Population	Total amount of male and female RCW including fledglings.
Potential New Breeding Pairs	Least value between number of males and number of females of breeding age.
Excess females lack of males	If the number of females of breeding age exceed the number of males of breeding age, the excess number of females will leave the managed area.
Potential Helpers (Potential Helpers con't)	The potential helpers is represented by a stock which increases if the number of males of breeding age exceeds the number of females of breeding age. Additionally, if the number of potential breeding pairs exceeds the number of clusters, then the potential breeding males will become part of the potential helper stock. The stock will decrease by the number of potential helpers which becomes actual helpers. This is a function of the number of potential helpers and the number of available useable cavities per cluster. The rate at which potential helpers will convert to helpers is limited by the smaller of the two influencing entities.
Helpers	1. Helpers is represented by a stock which increase by the number of potential helpers which becomes actual helpers. This rate is identical to the outflow of the potential helper stock. 2. The helpers stock will decrease if the number of cavities occupied by RCWs decrease. This suggest that the degradation of occupied cavities is the main influence in the decrease of helpers.
Total clusters	The total clusters is an entity defined by the number of usable number of cavities (defined in the cavity sub-model) divided by 5.437 (currently the number of cavities per cluster at Poinsett).
unoccupied usable cav\cluster	Simply defined as the acceptable number of cavities divided by the total number of clusters.

Clusters w\ o breeding pair	1. The Clusters w\ o breeding pair is represented by a stock which increases by the difference between the total number of clusters and the number of clusters with a breeding pair, provided there are two useable cavities per cluster without a breeding pair. 2. The stock will decrease by the number of clusters w/o breeding pair which converts to clusters with a breeding pair. This conversion is a function of the value of the Clusters w\ o breeding pair stock and the number of potential breeding pairs. The rate at which Clusters w\ o breeding pair will convert to Clusters w\ breeding pair is limited by the smaller of the two influencing entities.
Clusters w\ breeding pair	1. This entity is a stock which increases by the number of cluster w/o breeding pair converted to clusters w\breeding pair. This is the exact rate as the outflow of the cluster w\o breeding pair stock. 2. This stock decreases if the number of Clusters with a breeding pair is larger than the total number of clusters. The stock decreases by the difference of the clusters with breeding pair and the total number of clusters.
Excess f and m lack of clusters	If the number of potential new breeding pairs exceed the clusters without breeding pairs, there will be an excess of males and females.
Req basal area per bird	Each bird required a minimum amount of LLP trees present in order to gather its nutritional requirements. If the basal area per bird decreases, it is suggested that the RCW will lack in its nutritional requirements.
Basal area per bird	The amount of basal area per bird as determined by the model.
LLP forage area	Depends on the density of LLP 60 years and older.
LLP forage area per acre	Function of the basal area of LLP.
Total Acres	Number of acres of the area of management concern.
1. Total F Mortality 2. Total M Mortality	Total male and female deaths.
1. F Pop Change 2. M Pop Change	Change in the male and female population.
RCW Pop Change	The RCW population change was determined by subtracting all the outflows from the inflows for each age stock of the RCW.

Artificial Translocation entities	1. These entities represent the rate at which new RCWs are imported into the managed area. 2. Younger birds that are of breeding age will be translocated rather than older birds of breeding age. Thus, translocation will influence only the stock of RCWs that are ages 1to3 years of age.
1. Relatedness 2. Relatedness Index	These entities represent the general relationship are incorporated into the model to address the not well understood mechanisms which influences female departure due to the bird's instincts not to inbreed.
Acpt Avail Cav	1. This entity is a stock which is defined under the cavity sub-model. 2. This entity takes into consideration cavities loss due to competition with squirrels and other factors.

Appendix B

The following pages contain the structure of the system dynamics model utilized for the project. The model is divided into three sectors: tree, RCW, and cavity. See Chapter 4 for general comments regarding the model and Appendix A for assumptions made in constructing the model.



Tree
LLP 1to30 ideal stem dens
Area
excess LLP 1to30
LLP time bet thinning
LLP 1to30 stem dens
LLP 1to30 mech removal
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fire intensity
LLP 1to30 SPB infest
Total LLP 1to30 healt
LLP 1 to 30
LLP 1to30 % dth per burn
LLP 1to30 germ
LLP 1to30 mort
LLP 1to30 Ips beetle infest
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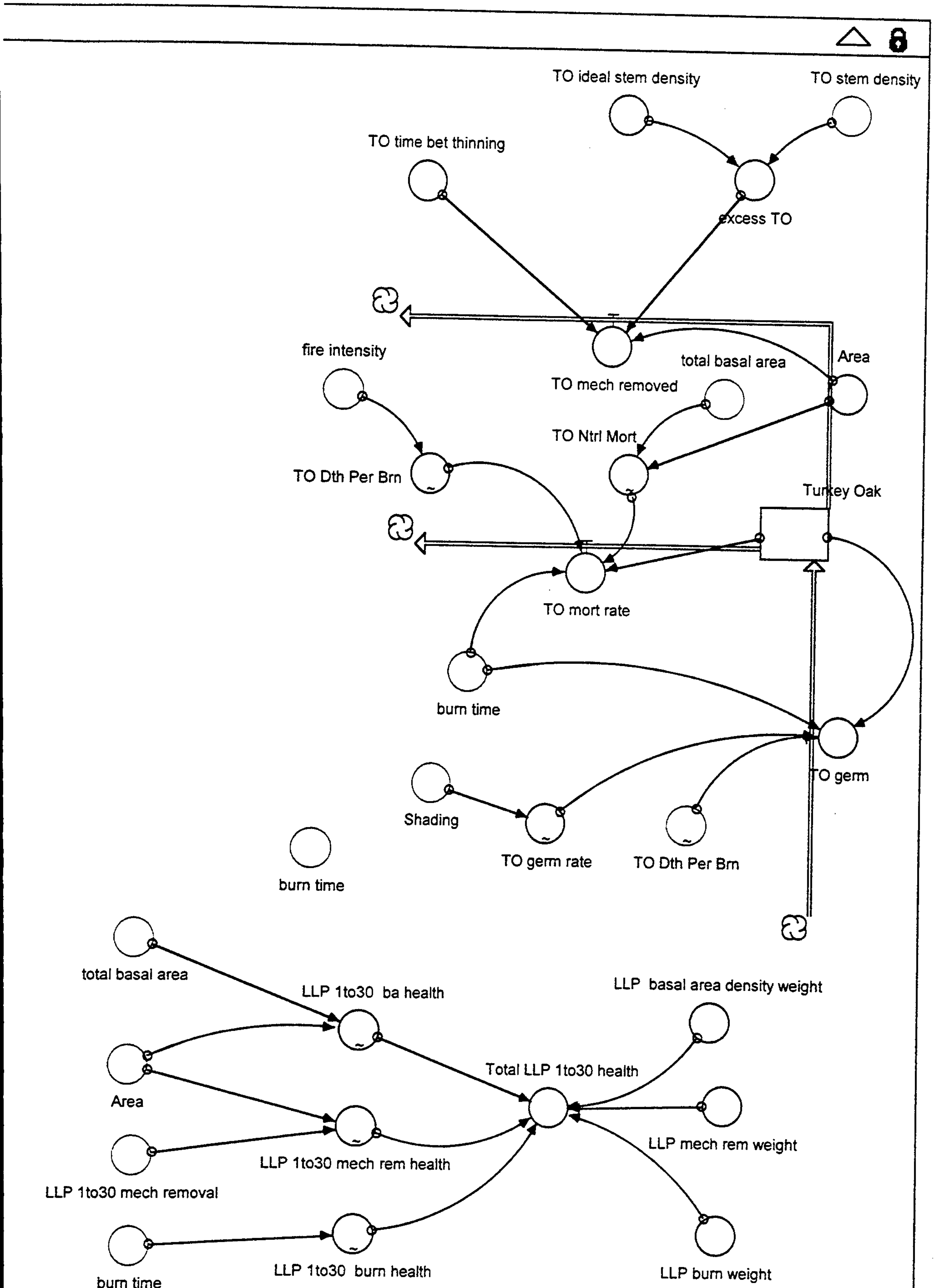
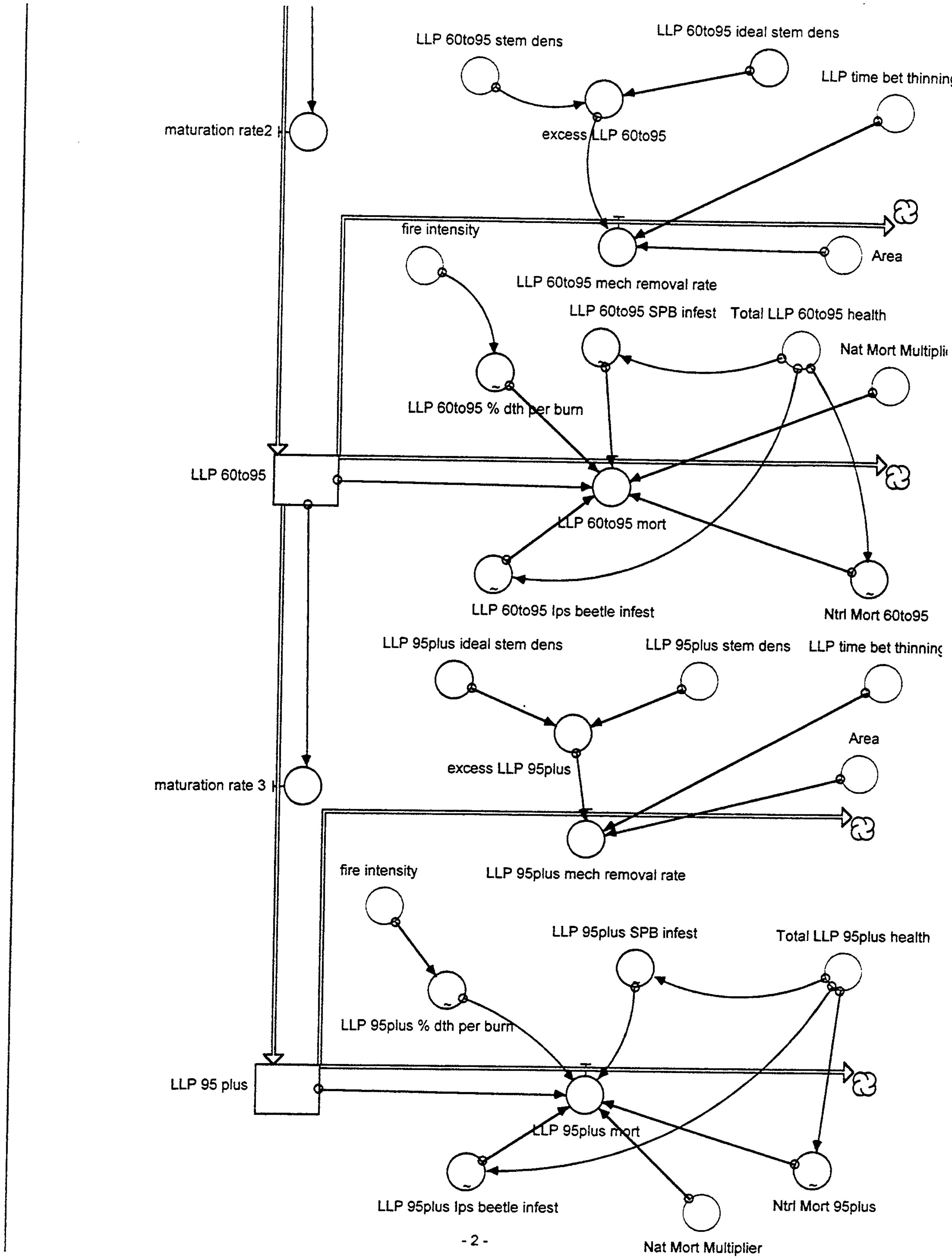
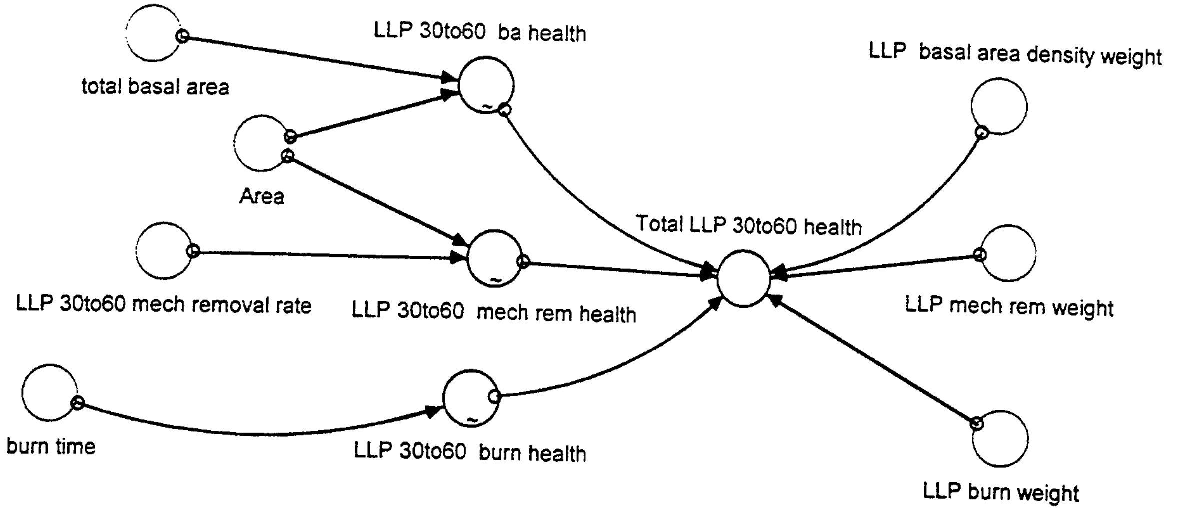
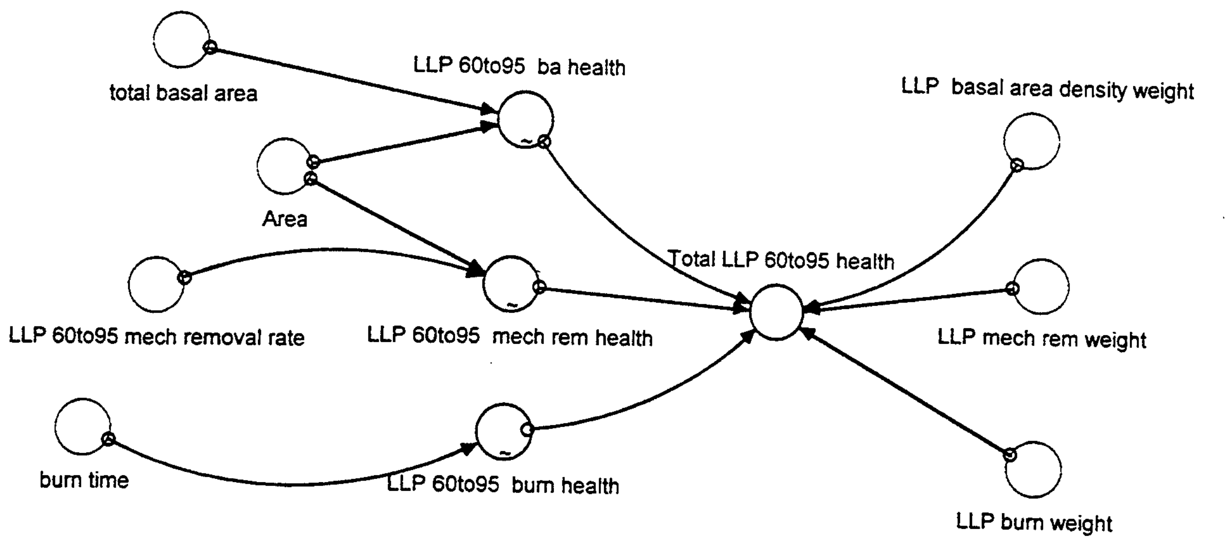
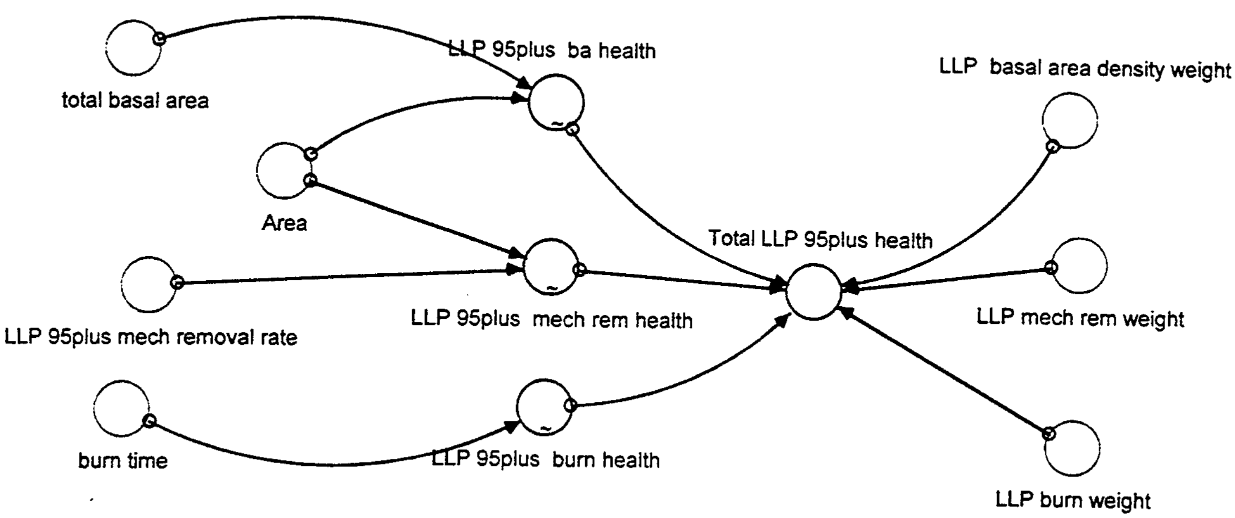
LLP germ
Mature LLP density
LLP 30to60 ideal stem dens
LLP 30to60 stem dens
LLP time bet thinning
Shading
excess LLP 30to60
maturation rate1
Area
fire intensity
LLP 30to60 mech removal rate
TO Shading
LLP Shading
LLP 30to60 SPB infest
Total LLP 30to60 health
TO stem density
LLP density
LLP 30to60 % dth per burn
LLP 30 to 60
LLP 30to60 mort rate
LLP 30to60 Ips beetle infest
Ntrl Mort 30to60
Nat Mort Multiplier
- 1 -

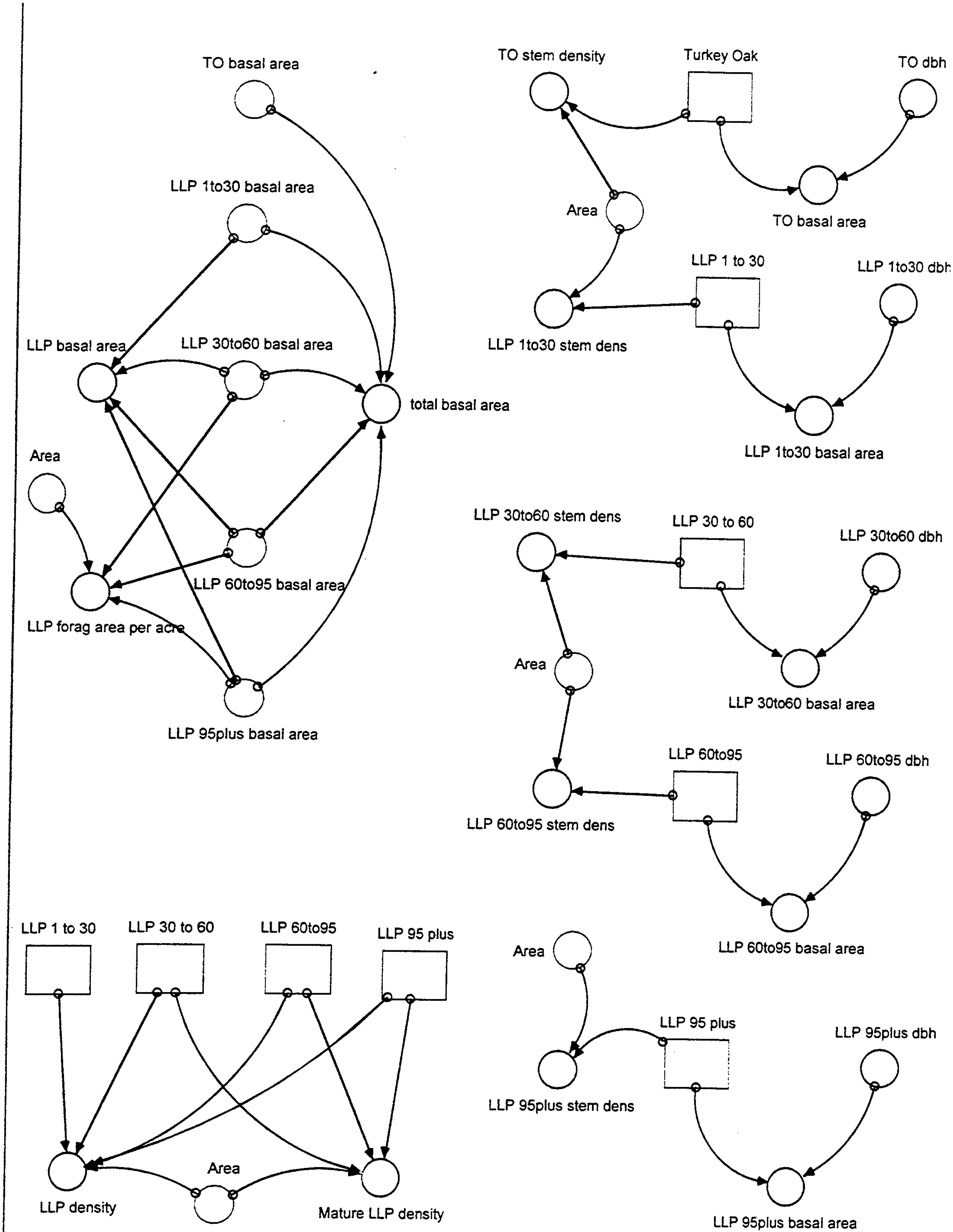

TO ideal stem density
TO stem density
TO time bet thinning
excess TO
fire intensity
TO mech removed
total basal area
Area
TO Ntrl Mort
TO Dth Per Brn
Turkey Oak
TO mort rate
burn time
TO germ
Shading
TO germ rate
TO Dth Per Brn
burn time
total basal area
LLP 1to30 ba health
LLP basal area density weight
Area
Total LLP 1to30 health
LLP mech rem weight
LLP 1to30 mech rem health
LLP 1to30 mech removal
burn time
LLP 1to30 burn health
LLP burn weight


LLP 60to95 stem dens
LLP 60to95 ideal stem dens
LLP time bet thinnin
maturation rate2
excess LLP 60to95
fire intensity
Area
LLP 60to95 mech removal rate
LLP 60to95 SPB infest
Total LLP 60to95 health
Nat Mort Multipli
LLP 60to95 % dth per burn
LLP 60to95
LLP 60to95 mort
LLP 60to95 Ips beetle infest
Ntrl Mort 60to95
LLP 95plus ideal stem dens
LLP 95plus stem dens
LLP time bet thinning
Area
excess LLP 95plus
maturation rate 3
fire intensity
LLP 95plus mech removal rate
LLP 95plus SPB infest
Total LLP 95plus health
LLP 95plus % dth per burn
LLP 95 plus
LLP 95plus mort
LLP 95plus Ips beetle infest
Ntrl Mort 95plus
Nat Mort Multiplier


total basal area
LLP 30to60 ba health
LLP basal area density weight
Area
Total LLP 30to60 health
LLP 30to60 mech removal rate
LLP 30to60 mech rem health
LLP mech rem weight
burn time
LLP 30to60 burn health
LLP burn weight


total basal area
LLP 60to95 ba health
LLP basal area density weight
Area
Total LLP 60to95 health
LLP 60to95 mech removal rate
LLP 60to95 mech rem health
LLP mech rem weight
burn time
LLP 60to95 burn health
LLP burn weight


total basal area
LLP 95plus ba health
LLP basal area density weight
Area
Total LLP 95plus health
LLP 95plus mech removal rate
LLP 95plus mech rem health
LLP mech rem weight
burn time
LLP 95plus burn health
LLP burn weight


TO basal area
LLP 1to30 basal area
LLP basal area
LLP 30to60 basal area
total basal area
Area
LLP 60to95 basal area
LLP forag area per acre
LLP 95plus basal area
TO stem density
Turkey Oak
TO dbh
Area
TO basal area
LLP 1 to 30
LLP 1to30 dbh
LLP 1to30 stem dens
LLP 1to30 basal area
LLP 30to60 stem dens
LLP 30 to 60
LLP 30to60 dbh
Area
LLP 30to60 basal area
LLP 60to95
LLP 60to95 dbh
LLP 60to95 stem dens
LLP 60to95 basal area
LLP 1 to 30
LLP 30 to 60
LLP 60to95
LLP 95 plus
Area
LLP density
Mature LLP density
Area
LLP 95 plus
LLP 95plus dbh
LLP 95plus stem dens
LLP 95plus basal area

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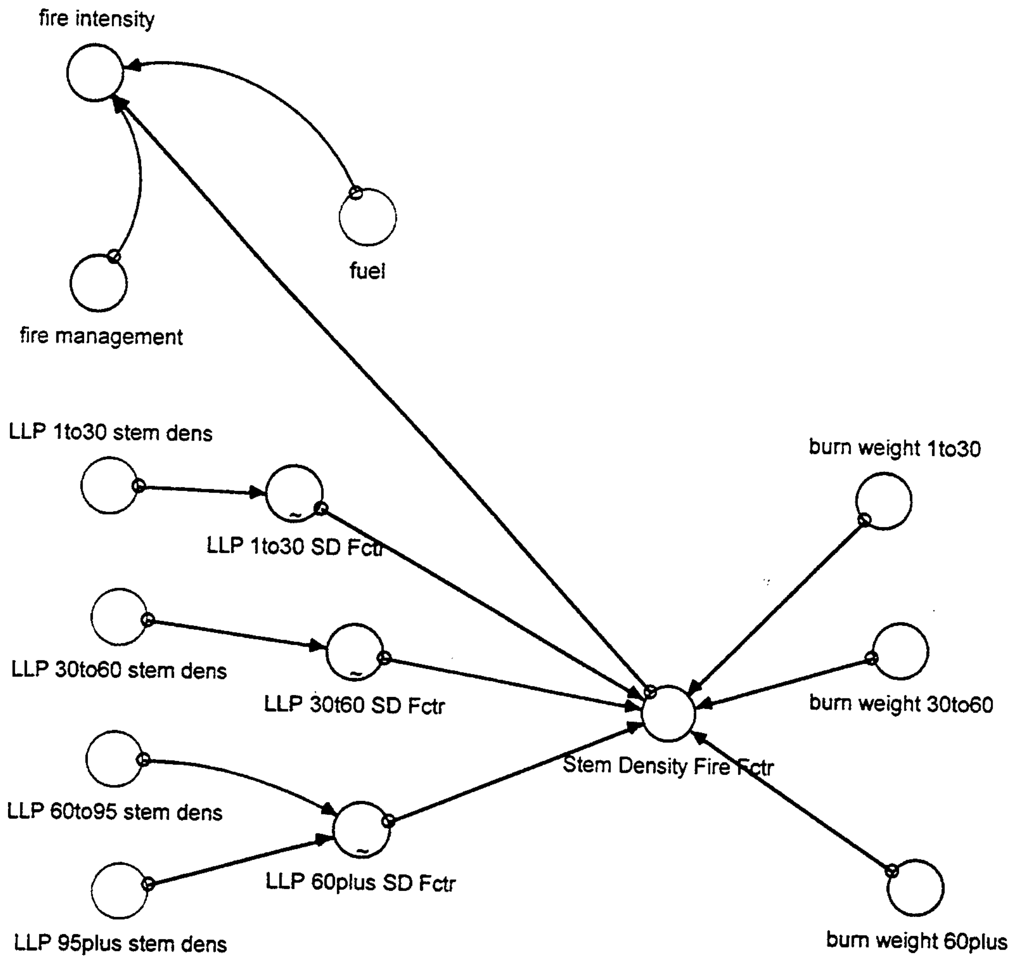
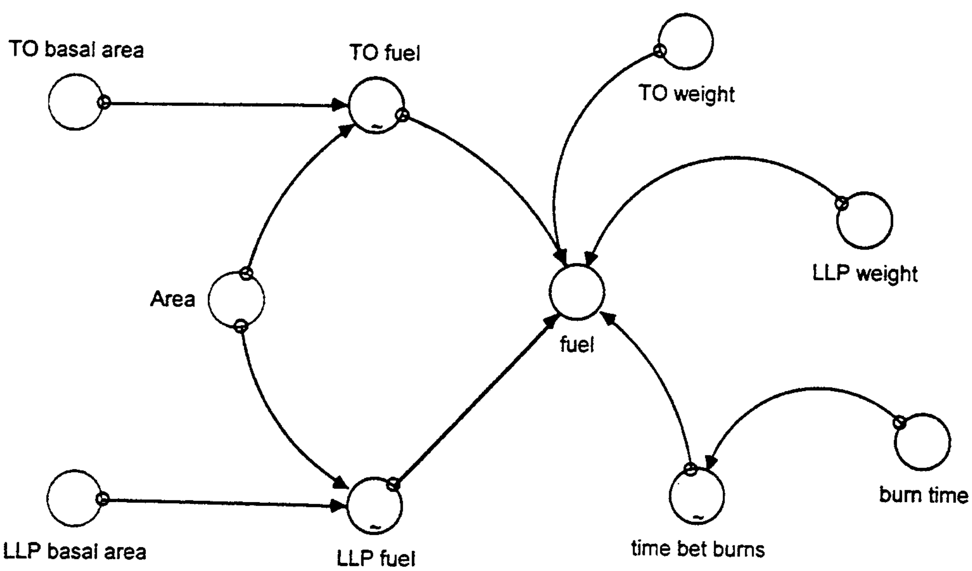

fire intensity
fuel
fire management
LLP 1to30 stem dens
LLP 1to30 SD Fctr
burn weight 1to30
LLP 30to60 stem dens
LLP 30t60 SD Fctr
burn weight 30to60
Stem Density Fire Fctr
LLP 60to95 stem dens
LLP 60plus SD Fctr
LLP 95plus stem dens
burn weight 60plus


TO basal area
TO fuel
TO weight
LLP weight
Area
fuel
burn time
LLP basal area
LLP fuel
time bet burns

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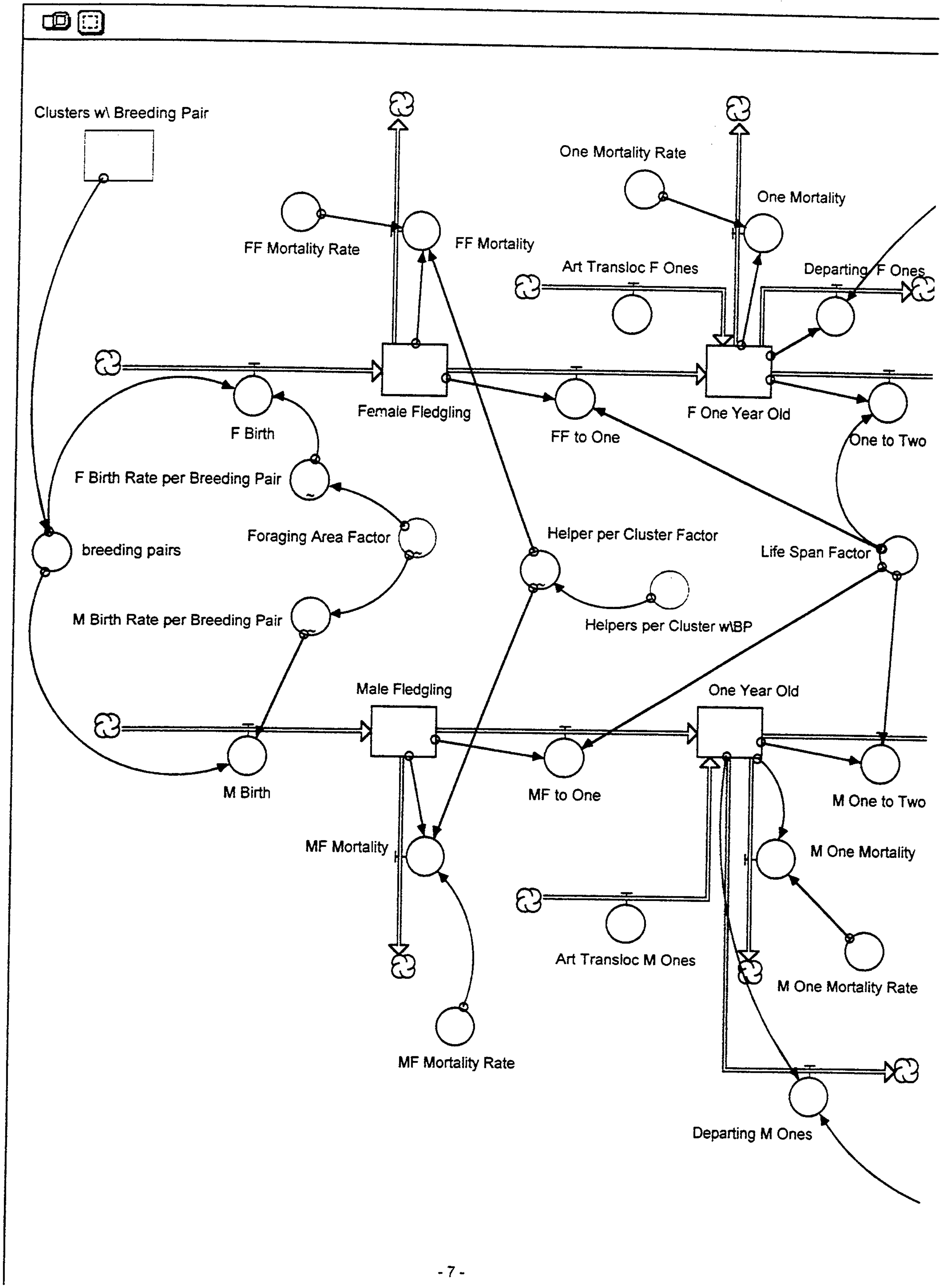
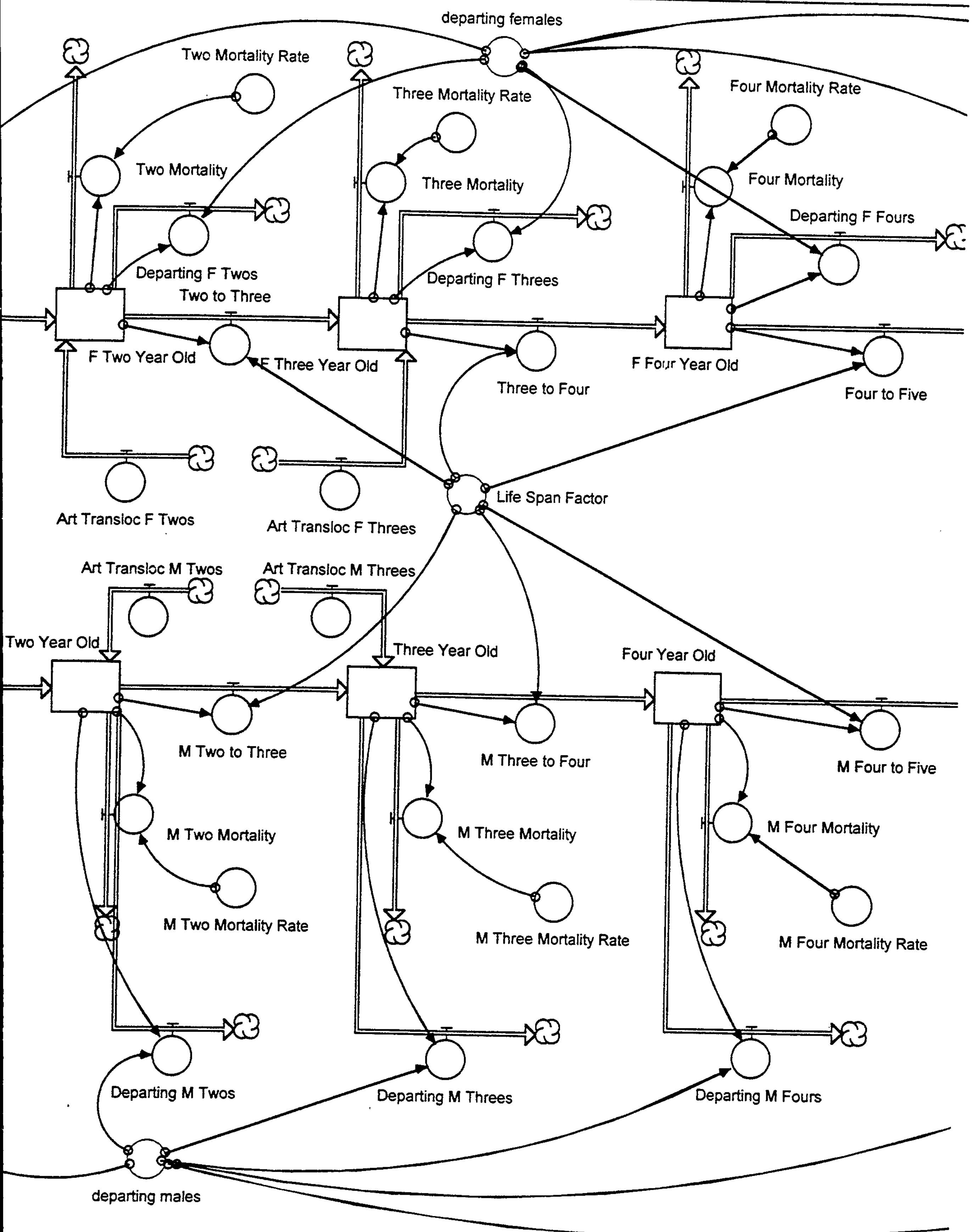
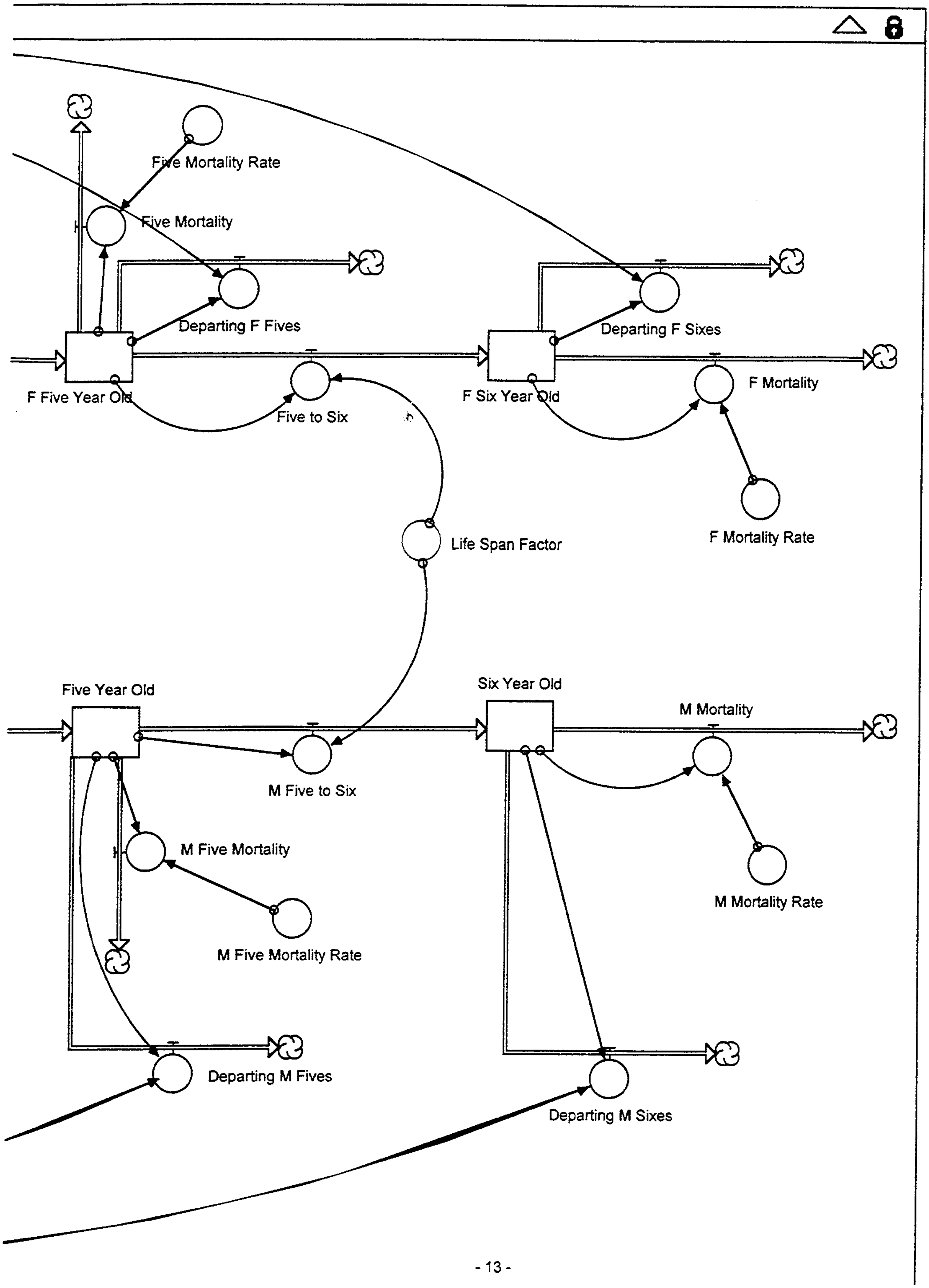
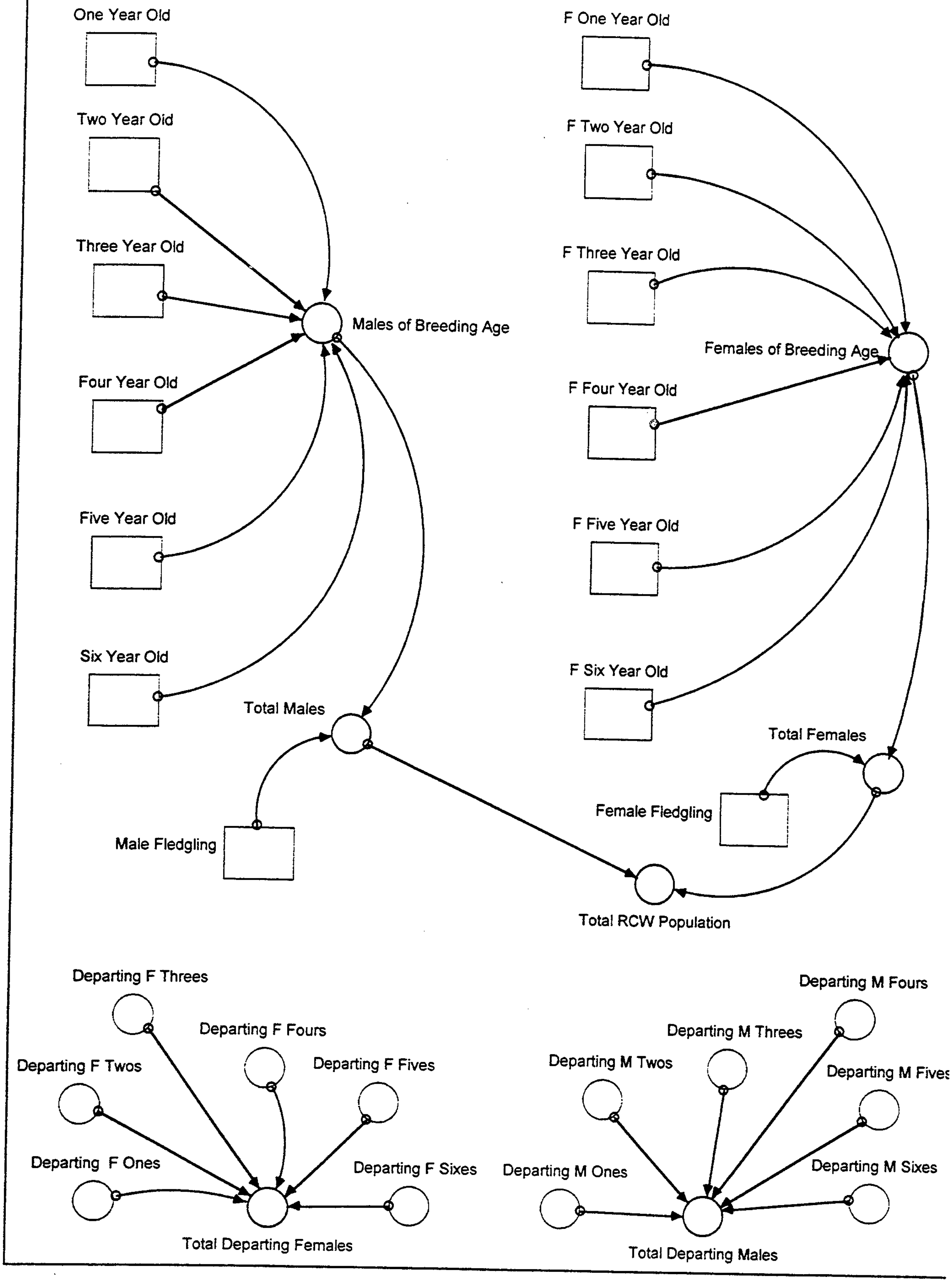
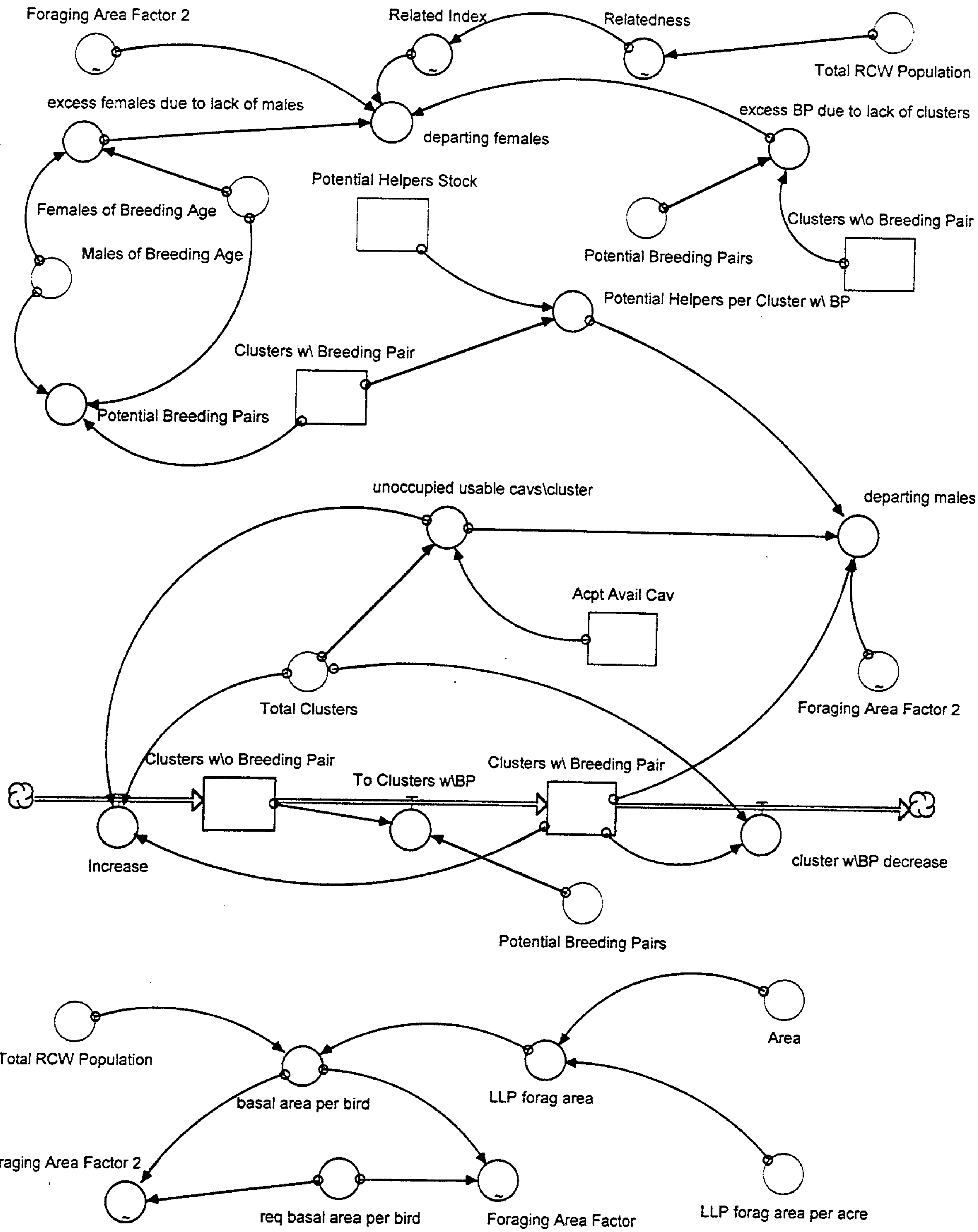

Clusters w\ Breeding Pair
One Mortality Rate
One Mortality
FF Mortality Rate
FF Mortality
Art Transloc F Ones
Departing F Ones
Female Fledgling
F One Year Old
F Birth
FF to One
One to Two
F Birth Rate per Breeding Pair
Foraging Area Factor
Helper per Cluster Factor
Life Span Factor
breeding pairs
Helpers per Cluster w\BP
M Birth Rate per Breeding Pair
Male Fledgling
One Year Old
M Birth
MF to One
M One to Two
MF Mortality
M One Mortality
Art Transloc M Ones
M One Mortality Rate
MF Mortality Rate
Departing M Ones

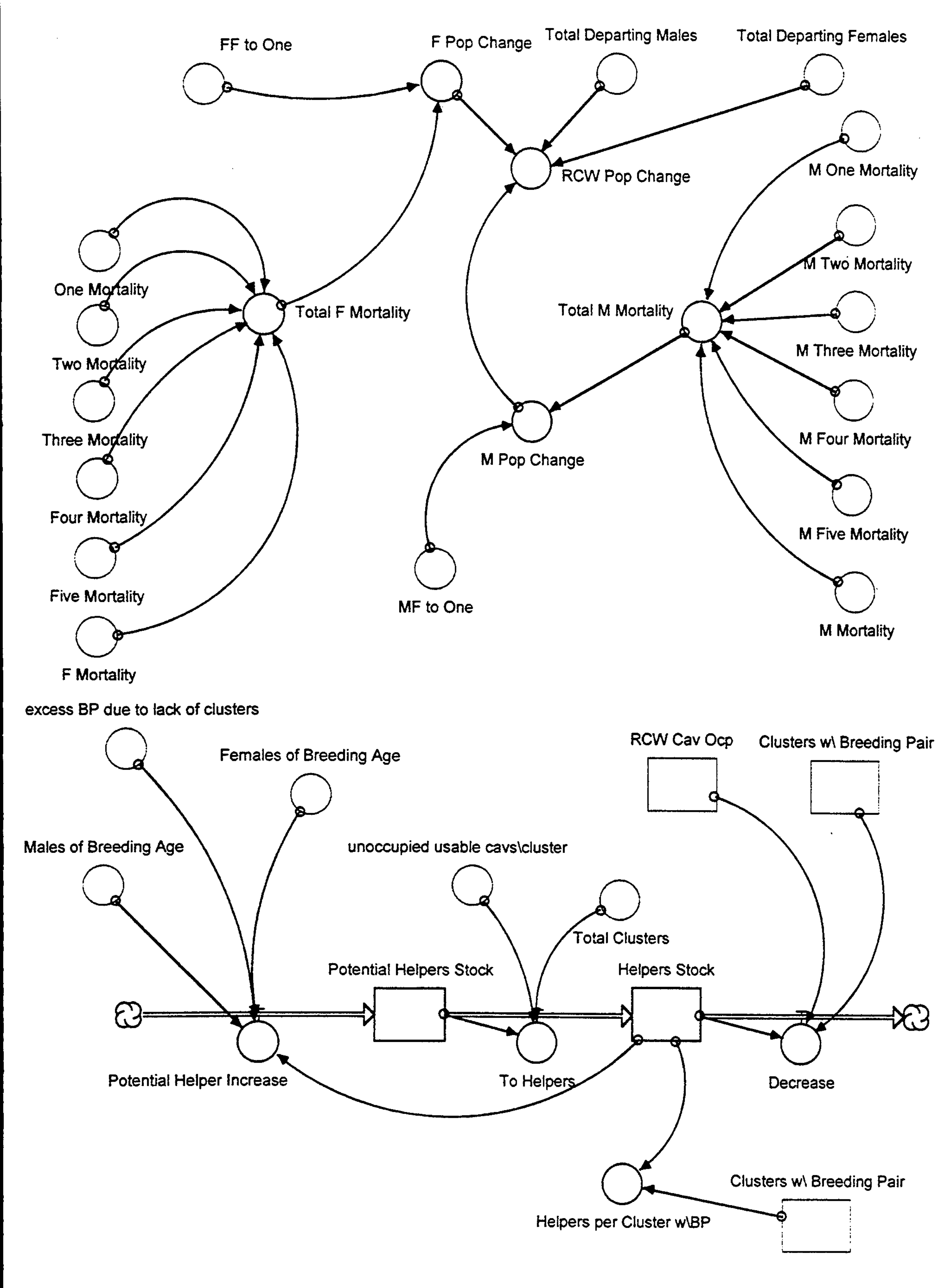

departing females
Two Mortality Rate
Three Mortality Rate
Four Mortality Rate
Two Mortality
Three Mortality
Four Mortality
Departing F Fours
Departing F Twos
Departing F Threes
Two to Three
F Two Year Old
F Three Year Old
F Four Year Old
Three to Four
Four to Five
Art Transloc F Twos
Art Transloc F Threes
Life Span Factor
Art Transloc M Twos
Art Transloc M Threes
Two Year Old
Three Year Old
Four Year Old
M Two to Three
M Three to Four
M Four to Five
M Two Mortality
M Three Mortality
M Four Mortality
M Two Mortality Rate
M Three Mortality Rate
M Four Mortality Rate
Departing M Twos
Departing M Threes
Departing M Fours
departing males


Five Mortality Rate
Five Mortality
Departing F Fives
Departing F Sixes
F Five Year Old
Five to Six
F Six Year Old
F Mortality
Life Span Factor
F Mortality Rate
Five Year Old
Six Year Old
M Mortality
M Five to Six
M Five Mortality
M Mortality Rate
M Five Mortality Rate
Departing M Fives
Departing M Sixes


One Year Old
Two Year Old
Three Year Old
Four Year Old
Five Year Old
Six Year Old
Males of Breeding Age
Total Males
Male Fledgling
F One Year Old
F Two Year Old
F Three Year Old
F Four Year Old
F Five Year Old
F Six Year Old
Females of Breeding Age
Total Females
Female Fledgling
Total RCW Population
Departing F Threes
Departing F Fours
Departing F Twos
Departing F Fives
Departing F Ones
Departing F Sixes
Total Departing Females
Departing M Fours
Departing M Threes
Departing M Twos
Departing M Fives
Departing M Ones
Departing M Sixes
Total Departing Males



Foraging Area Factor 2
Related Index
Relatedness
Total RCW Population
excess females due to lack of males
departing females
excess BP due to lack of clusters
Potential Helpers Stock
Females of Breeding Age
Males of Breeding Age
Clusters w\o Breeding Pair
Potential Breeding Pairs
Potential Helpers per Cluster w\ BP
Clusters w\ Breeding Pair
Potential Breeding Pairs
unoccupied usable cavs\cluster
departing males
Acpt Avail Cav
Total Clusters
Foraging Area Factor 2
Clusters w\o Breeding Pair
Clusters w\ Breeding Pair
To Clusters w\BP
Increase
cluster w\BP decrease
Potential Breeding Pairs
Total RCW Population
Area
basal area per bird
LLP forag area
Foraging Area Factor 2
req basal area per bird
Foraging Area Factor
LLP forag area per acre


FF to One
F Pop Change
Total Departing Males
Total Departing Females
RCW Pop Change
M One Mortality
One Mortality
Total F Mortality
M Two Mortality
Total M Mortality
Two Mortality
M Three Mortality
Three Mortality
M Four Mortality
M Pop Change
Four Mortality
M Five Mortality
Five Mortality
MF to One
M Mortality
F Mortality
excess BP due to lack of clusters
RCW Cav Ocp
Clusters w\ Breeding Pair
Females of Breeding Age
Males of Breeding Age
unoccupied usable cavs\cluster
Total Clusters
Potential Helpers Stock
Helpers Stock
Potential Helper Increase
To Helpers
Decrease
Clusters w\ Breeding Pair
Helpers per Cluster w\BP

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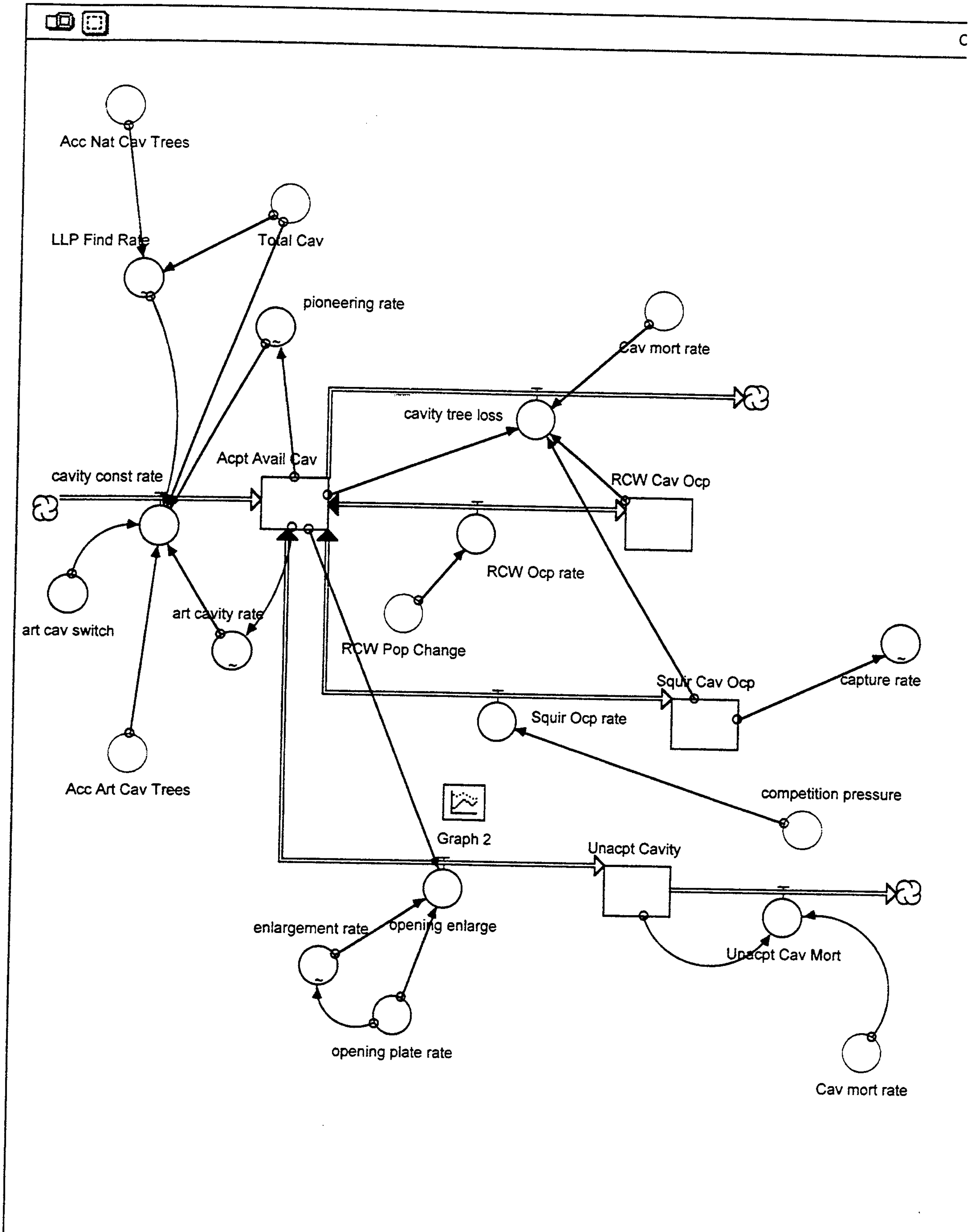
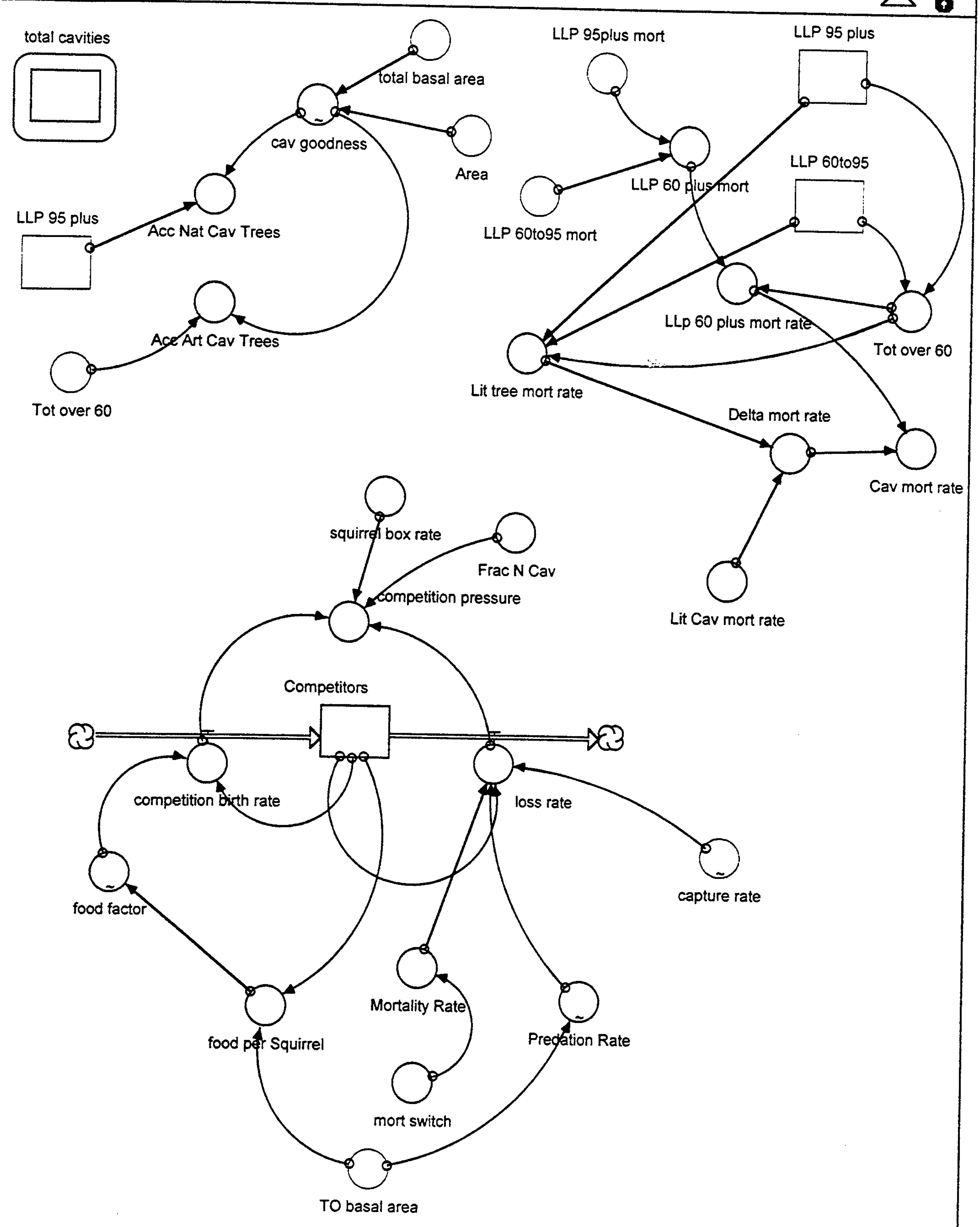

Acc Nat Cav Trees
LLP Find Rate
Total Cav
pioneering rate
Cav mort rate
cavity tree loss
Acpt Avail Cav
cavity const rate
RCW Cav Ocp
RCW Ocp rate
art cav switch
art cavity rate
RCW Pop Change
Squir Cav Ocp
capture rate
Squir Ocp rate
Acc Art Cav Trees
competition pressure
Graph 2
Unacpt Cavity
enlargement rate
opening enlarge
Unacpt Cav Mort
opening plate rate
Cav mort rate


total cavities
total basal area
cav goodness
Area
LLP 95 plus
Acc Nat Cav Trees
Acc Art Cav Trees
Tot over 60
LLP 95plus mort
LLP 95 plus
LLP 60 plus mort
LLP 60to95
LLP 60to95 mort
LLp 60 plus mort rate
Tot over 60
Lit tree mort rate
Delta mort rate
Cav mort rate
Lit Cav mort rate
squirrel box rate
Frac N Cav
competition pressure
Competitors
competition birth rate
loss rate
capture rate
food factor
Mortality Rate
Predation Rate
food per Squirrel
mort switch
TO basal area

Appendix C

The following pages contain the equations and values employed in the system dynamics model utilized for the project. See Chapter 4 for general comments regarding the model and Appendix A for assumptions made in constructing the model.

Cavity

☐ Acpt_Avail_Cav(t) = Acpt_Avail_Cav(t - dt) + (cavity_const_rate - RCW_Ocp_rate - cavity_tree_loss - Squir_Ocp_rate - opening_enlarge) * dt
INIT Acpt_Avail_Cav = 54

DOCUMENT: Cavities that are not enlarged nor occupied.

INFLOWS:

cavity_const_rate = MIN((Acc_Art_Cav_Trees-Total_Cav),((art_cav_switch*art_cavity_rate)+(pioneering_rate*LLP_Find_Rate)))
DOCUMENT: Maximum artifical cavity construction rate per year in every tree possible. Takes minumum of holeless trees or number of constructed cavities by pioneering and artificial construction.

OUTFLOWS:

RCW_Ocp_rate = RCW_Pop_Change
DOCUMENT: Birds per year. Each bird is assumed to occupy one cavity.

cavity_tree_loss = (Acpt_Avail_Cav+RCW_Cav_Ocp+Squir_Cav_Ocp)*Cav_mort_rate
DOCUMENT: Cavity trees killed per year.

Squir_Ocp_rate = competition_pressure
DOCUMENT: Cavities occupied by squirrels per year.

opening_enlarge = (enlargement_rate*Acpt_Avail_Cav)-opening_plate_rate

☐ Competitors(t) = Competitors(t - dt) + (competition_birth_rate - loss_rate) * dt
INIT Competitors = 30

INFLOWS:

competition_birth_rate = Competitors*1.5*food_factor
DOCUMENT: According to (Sawyer:1985) squirrels have two litters per year of about 2.5 squirrels per litter. Therefore, each breeding pair would produce 5 squirrels per year and each squirrel would produce 2.5 squirrels per year.

OUTFLOWS:

loss_rate = Competitors*(Mortality_Rate+Predation_Rate)+capture_rate

☐ RCW_Cav_Ocp(t) = RCW_Cav_Ocp(t - dt) + (RCW_Ocp_rate) * dt
INIT RCW_Cav_Ocp = 12

DOCUMENT: Number of cavities occupied by RCWs.

INFLOWS:

RCW_Ocp_rate = RCW_Pop_Change
DOCUMENT: Birds per year. Each bird is assumed to occupy one cavity.

Squir_Cav_Ocp(t) = Squir_Cav_Ocp(t - dt) + (Squir_Ocp_rate) * dt
INIT Squir_Cav_Ocp = 20

DOCUMENT: Number of cavities occupied by squirrels.

INFLOWS:

Squir_Ocp_rate = competition_pressure
DOCUMENT: Cavities occupied by squirrels per year.

Unacpt_Cavity(t) = Unacpt_Cavity(t - dt) + (opening_enlarge - Unacpt_Cav_Mort) * dt
INIT Unacpt_Cavity = 20

DOCUMENT: Number of cavities enlarged by pileated woodpeckers.

INFLOWS:

opening_enlarge = (enlargement_rate*Acpt_Avail_Cav)-opening_plate_rate

OUTFLOWS:

Unacpt_Cav_Mort = Unacpt_Cavity*Cav_mort_rate

Acc_Art_Cav_Trees = Tot_over_60*cav_goodness
Acc_Nat_Cav_Trees = LLP_95_plus*cav_goodness
art_cav_switch = 1
Cav_mort_rate = LLp_60_plus_mort_rate+Delta_mort_rate
competition_pressure = (((competition_birth_rate-loss_rate)*Frac_N_Cav))-squirrel_box_rate
Delta_mort_rate = Lit_Cav_mort_rate-Lit_tree_mort_rate
food_per_Squirrel = TO_basal_area/Competitors
Frac_N_Cav = .67
DOCUMENT: 2/3 of the squirrels live in RCW cavities vs other nesting sites

Lit_Cav_mort_rate = .013
DOCUMENT: Conner and others mortality rate based on 7-year study. This rate is slightly higher than normal LLP mortality. (deaths/tree/year)

Lit_tree_mort_rate = (LLP_60to95*.0075+LLP_95_plus*.0138)/Tot_over_60
DOCUMENT: Death rate of two stocks of non-cavity trees weithted by their popluation.

LLP_60_plus_mort = (LLP_95plus_mort+LLP_60to95_mort)
LLp_60_plus_mort_rate = LLP_60_plus_mort/Tot_over_60
Mortality_Rate = .7*mort_switch
mort_switch = 1
opening_plate_rate = 0
DOCUMENT: opening plates installed per year

squirrel_box_rate = 0
DOCUMENT: Rate of squirrel boxes installed each year.

Tot_over_60 = LLP_95_plus+LLP_60to95

art_cavity_rate = GRAPH(Acpt_Avail_Cav)
(0.00, 19.9), (3.00, 13.1), (6.00, 9.90), (9.00, 7.20), (12.0, 5.40), (15.0, 4.30), (18.0, 3.30), (21.0, 1.80), (24.0, 0.7), (27.0, 0.3), (30.0, 0.00)
DOCUMENT: Number artificial cavities created each year based on available acceptable cavities.

capture_rate = GRAPH(Squir_Cav_Ocp)
(20.0, 0.00), (28.0, 8.00), (36.0, 12.0), (44.0, 22.5), (52.0, 27.5), (60.0, 36.0), (68.0, 49.5), (76.0, 60.5), (84.0, 75.0), (92.0, 86.0), (100, 99.0)
DOCUMENT: Squirrels captured per year.

cav_goodness = GRAPH(total_basal_area/Area)
(0.00, 0.00), (14.0, 0.155), (28.0, 0.24), (42.0, 0.47), (56.0, 0.93), (70.0, 0.99), (84.0, 0.965), (98.0, 0.895), (112, 0.65), (126, 0.165), (140, 0.05)

enlargement_rate = GRAPH(opening_plate_rate)
(0.00, 0.0318), (10.0, 0.0267), (20.0, 0.023), (30.0, 0.0189), (40.0, 0.0158), (50.0, 0.0118), (60.0, 0.00832), (70.0, 0.00592), (80.0, 0.00384), (90.0, 0.00224), (100, 0.00)
DOCUMENT: enlargement/tree/year (p. 535, Connor & others 1991)

food_factor = GRAPH(food_per_Squirrel)
(0.00, 0.00), (2.00, 0.335), (4.00, 0.625), (6.00, 0.735), (8.00, 0.835), (10.0, 0.885), (12.0, 0.92), (14.0, 0.94), (16.0, 0.97), (18.0, 0.98), (20.0, 0.99)

LLP_Find_Rate = GRAPH(Acc_Nat_Cav_Trees-Total_Cav)
(0.00, 0.00), (10.0, 0.00), (20.0, 0.035), (30.0, 0.1), (40.0, 0.195), (50.0, 0.3), (60.0, 0.4), (70.0, 0.505), (80.0, 0.665), (90.0, 0.81), (100, 0.995)
DOCUMENT: Fraction of acceptable trees without cavites found per year.

pioneering_rate = GRAPH(Acpt_Avail_Cav)
(0.00, 2.99), (1.00, 1.67), (2.00, 1.01), (3.00, 0.765), (4.00, 0.6), (5.00, 0.48), (6.00, 0.345), (7.00, 0.225), (8.00, 0.15), (9.00, 0.09), (10.0, 0.00)
DOCUMENT: Number of trees pioneered each year based on available acceptable cavities.

Predation_Rate = GRAPH(TO_basal_area)
(0.00, 0.985), (5000, 0.85), (10000, 0.75), (15000, 0.635), (20000, 0.575), (25000, 0.515), (30000, 0.475), (35000, 0.385), (40000, 0.325), (45000, 0.25), (50000, 0.195)
DOCUMENT: As we reduce TO density, FS will be more susceptable to predation

total cavities

Total_Cav = Acpt_Avail_Cav+RCW_Cav_Ocp+Squir_Cav_Ocp+Unacpt_Cavity

Total_Clusters = Useable_Cav/5.437
DOCUMENT: According to Shaw personnel, there are 5.437 cavities per cluster.

unoccupied_usable_cav\cluster = Acpt_Avail_Cav/Total_Clusters
Useable_Cav = Total_Cav-Unacpt_Cavity

RCW Population

Clusters_w\o_Breeding_Pair(t) = Clusters_w\o_Breeding_Pair(t - dt) + (Increase - To_Clusters_w\BP) * dt
INIT Clusters_w\o_Breeding_Pair = 0
INFLOWS:
Increase = IF(unoccupied_usable_cavs\cluster>2)THEN(Total_Clusters-Clusters_w_Breeding_Pair)ELSE(0)
OUTFLOWS:
To_Clusters_w\BP = IF(Clusters_w\o_Breeding_Pair>Potential_Breeding_Pairs)THEN(Potential_Breeding_Pairs)ELSE(Clusters_w\o_Breeding_Pair)

Clusters_w_Breeding_Pair(t) = Clusters_w_Breeding_Pair(t - dt) + (To_Clusters_w\BP - cluster_w\BP_decrease) * dt
INIT Clusters_w_Breeding_Pair = 0
INFLOWS:
To_Clusters_w\BP = IF(Clusters_w\o_Breeding_Pair>Potential_Breeding_Pairs)THEN(Potential_Breeding_Pairs)ELSE(Clusters_w\o_Breeding_Pair)
OUTFLOWS:
cluster_w\BP_decrease = IF(Clusters_w_Breeding_Pair>Total_Clusters)THEN(Clusters_w_Breeding_Pair-Total_Clusters)ELSE(0)

Female_Fledgling(t) = Female_Fledgling(t - dt) + (F_Birth - FF_to_One - FF_Mortality) * dt
INIT Female_Fledgling = 3
INFLOWS:
F_Birth = breeding_pairs*F_Birth_Rate_per_Breeding_Pair
OUTFLOWS:
FF_to_One = Female_Fledgling/Life_Span_Factor
FF_Mortality = Female_Fledgling*FF_Mortality_Rate*Helper_per_Cluster_Factor

Five_Year_Old(t) = Five_Year_Old(t - dt) + (M_Four_to_Five - M_Five_to_Six - M_Five_Mortality - Departing_M_Fives) * dt
INIT Five_Year_Old = 0
INFLOWS:
M_Four_to_Five = Four_Year_Old/Life_Span_Factor
OUTFLOWS:
M_Five_to_Six = Five_Year_Old/Life_Span_Factor
M_Five_Mortality = Five_Year_Old*M_Five_Mortality_Rate
Departing_M_Fives = IF(Five_Year_Old<departing_males/6)THEN(Five_Year_Old)ELSE(departing_males/6)

☐ Four_Year_Old(t) = Four_Year_Old(t - dt) + (M_Three_to_Four - M_Four_to_Five - M_Four_Mortality - Departing_M_Fours) * dt
INIT Four_Year_Old = 0
INFLOWS:
M_Three_to_Four = Three_Year_Old/Life_Span_Factor
OUTFLOWS:
M_Four_to_Five = Four_Year_Old/Life_Span_Factor
M_Four_Mortality = Four_Year_Old*M_Four_Mortality_Rate
Departing_M_Fours = IF(Four_Year_Old<departing_males/6)THEN(Four_Year_Old)ELSE(departing_males/6)

☐ F_Five_Year_Old(t) = F_Five_Year_Old(t - dt) + (Four_to_Five - Five_to_Six - Five_Mortality - Departing_F_Fives) * dt
INIT F_Five_Year_Old = 1
INFLOWS:
Four_to_Five = F_Four_Year_Old/Life_Span_Factor
OUTFLOWS:
Five_to_Six = F_Five_Year_Old/Life_Span_Factor
Five_Mortality = F_Five_Year_Old*Five_Mortality_Rate
Departing_F_Fives = IF(F_Five_Year_Old<departing_females/6)THEN(F_Five_Year_Old)ELSE(departing_females/6)

☐ F_Four_Year_Old(t) = F_Four_Year_Old(t - dt) + (Three_to_Four - Four_to_Five - Four_Mortality - Departing_F_Fours) * dt
INIT F_Four_Year_Old = 1
INFLOWS:
Three_to_Four = F_Three_Year_Old/Life_Span_Factor
OUTFLOWS:
Four_to_Five = F_Four_Year_Old/Life_Span_Factor
Four_Mortality = F_Four_Year_Old*Four_Mortality_Rate
Departing_F_Fours = IF(F_Four_Year_Old<departing_females/6)THEN(F_Four_Year_Old)ELSE(departing_females/6)

☐ F_One_Year_Old(t) = F_One_Year_Old(t - dt) + (FF_to_One + Art_Transloc_F_Ones - One_to_Two - One_Mortality - Departing__F_Ones) * dt
INIT F_One_Year_Old = 1
INFLOWS:
FF_to_One = Female_Fledgling/Life_Span_Factor
Art_Transloc_F_Ones = 0
OUTFLOWS:
One_to_Two = F_One_Year_Old/Life_Span_Factor
One_Mortality = F_One_Year_Old*One_Mortality_Rate
Departing__F_Ones = IF(F_One_Year_Old<departing_females/6)THEN(F_One_Year_Old)ELSE(departing_females/6)

☐ F_Six_Year_Old(t) = F_Six_Year_Old(t - dt) + (Five_to_Six - F_Mortality - Departing_F_Sixes) * dt
INIT F_Six_Year_Old = 1
INFLOWS:
Five_to_Six = F_Five_Year_Old/Life_Span_Factor
OUTFLOWS:
F_Mortality = F_Six_Year_Old*F_Mortality_Rate
Departing_F_Sixes =
IF(F_Six_Year_Old<F_Six_Year_Old/6)THEN(F_Six_Year_Old)ELSE(departing_females/6)

☐ F_Three_Year_Old(t) = F_Three_Year_Old(t - dt) + (Two_to_Three + Art_Transloc_F_Threes - Three_to_Four - Three_Mortality - Departing_F_Threes) * dt
INIT F_Three_Year_Old = 0
INFLOWS:
Two_to_Three = F_Two_Year_Old/Life_Span_Factor
Art_Transloc_F_Threes = 0
OUTFLOWS:
Three_to_Four = F_Three_Year_Old/Life_Span_Factor
Three_Mortality = F_Three_Year_Old*Three_Mortality_Rate
Departing_F_Threes =
IF(F_Three_Year_Old<departing_females/6)THEN(F_Three_Year_Old)ELSE(departing_females/6)

☐ F_Two_Year_Old(t) = F_Two_Year_Old(t - dt) + (One_to_Two + Art_Transloc_F_Twos - Two_to_Three - Two_Mortality - Departing_F_Twos) * dt
INIT F_Two_Year_Old = 2
INFLOWS:
One_to_Two = F_One_Year_Old/Life_Span_Factor
Art_Transloc_F_Twos = 0
OUTFLOWS:
Two_to_Three = F_Two_Year_Old/Life_Span_Factor
Two_Mortality = F_Two_Year_Old*Two_Mortality_Rate
Departing_F_Twos =
IF(F_Two_Year_Old<departing_females/6)THEN(F_Two_Year_Old)ELSE(departing_females/6)

☐ Helpers_Stock(t) = Helpers_Stock(t - dt) + (To_Helpers - Decrease) * dt
INIT Helpers_Stock = 0
INFLOWS:
To_Helpers =
IF(unoccupied_usable_cavs\cluster*Total_Clusters>Potential_Helpers_Stock)THEN(Potential_Helpers_Stock)ELSE(unoccupied_usable_cavs\cluster*Total_Clusters)
OUTFLOWS:
Decrease =
IF(Helpers_Stock>(RCW_Cav_Ocp-Clusters_w_Breeding_Pair))THEN(Helpers_Stock)-(RCW_Cav_Ocp-Clusters_w_Breeding_Pair)ELSE(0)

☐ Male_Fledgling(t) = Male_Fledgling(t - dt) + (M_Birth - MF_to_One - MF_Mortality) * dt
INIT Male_Fledgling = 1
INFLOWS:

M_Birth = breeding_pairs*M_Birth_Rate_per_Breeding_Pair
OUTFLOWS:
MF_to_One = Male_Fledgling/Life_Span_Factor
MF_Mortality = Male_Fledgling*MF_Mortality_Rate*Helper_per_Cluster_Factor

One_Year_Old(t) = One_Year_Old(t - dt) + (MF_to_One + Art_Transloc_M_Ones - M_One_to_Two - M_One_Mortality - Departing_M_Ones) * dt
INIT One_Year_Old = 1
INFLOWS:
MF_to_One = Male_Fledgling/Life_Span_Factor
Art_Transloc_M_Ones = 0
OUTFLOWS:
M_One_to_Two = One_Year_Old/Life_Span_Factor
M_One_Mortality = One_Year_Old*M_One_Mortality_Rate
Departing_M_Ones =
IF(One_Year_Old<departing_males/6)THEN(One_Year_Old)ELSE(departing_males/6)

Potential_Helpers_Stock(t) = Potential_Helpers_Stock(t - dt) + (Potential_Helper_Increase - To_Helpers) * dt
INIT Potential_Helpers_Stock = 0
INFLOWS:
Potential_Helper_Increase =
IF(Males_of_Breeding_Age-Helpers_Stock>Females_of_Breeding_Age)THEN(Males_of_Breeding_Age-Helpers_Stock-Females_of_Breeding_Age+excess_BP_due_to_lack_of_clusters)ELSE(excess_BP_due_to_lack_of_clusters)
OUTFLOWS:
To_Helpers =
IF(unoccupied_usable_cavs\cluster*Total_Clusters>Potential_Helpers_Stock)THEN(Potential_Helpers_Stock)ELSE(unoccupied_usable_cavs\cluster*Total_Clusters)

Six_Year_Old(t) = Six_Year_Old(t - dt) + (M_Five_to_Six - M_Mortality - Departing_M_Sixes) * dt
INIT Six_Year_Old = 0
INFLOWS:
M_Five_to_Six = Five_Year_Old/Life_Span_Factor
OUTFLOWS:
M_Mortality = Six_Year_Old*M_Mortality_Rate
Departing_M_Sixes =
IF(Six_Year_Old<departing_males/6)THEN(Six_Year_Old)ELSE(departing_males/6)

Three_Year_Old(t) = Three_Year_Old(t - dt) + (M_Two_to_Three + Art_Transloc_M_Threes - M_Three_to_Four - M_Three_Mortality - Departing_M_Threes) * dt
INIT Three_Year_Old = 3
INFLOWS:
M_Two_to_Three = Two_Year_Old/Life_Span_Factor
Art_Transloc_M_Threes = 0
OUTFLOWS:
M_Three_to_Four = Three_Year_Old/Life_Span_Factor
M_Three_Mortality = Three_Year_Old*M_Three_Mortality_Rate

Departing_M_Threes =
IF(Three_Year_Old<departing_males/6)THEN(Three_Year_Old)ELSE(departing_males/6)

Two_Year_Old(t) = Two_Year_Old(t - dt) + (M_One_to_Two + Art_Transloc_M_Twos - M_Two_to_Three - M_Two_Mortality - Departing_M_Twos) * dt
INIT Two_Year_Old = 2
INFLOWS:
M_One_to_Two = One_Year_Old/Life_Span_Factor
Art_Transloc_M_Twos = 0
OUTFLOWS:
M_Two_to_Three = Two_Year_Old/Life_Span_Factor
M_Two_Mortality = Two_Year_Old*M_Two_Mortality_Rate
Departing_M_Twos =
IF(Two_Year_Old<departing_males/6)THEN(Two_Year_Old)ELSE(departing_males/6)

basal_area_per_bird = LLP_forag_area/Total_RCW_Population

breeding_pairs = Clusters_w_Breeding_Pair

departing_females =
(excess_BP_due_to_lack_of_clusters+excess_females_due_to_lack_of_males)*Foraging_Area_Facto r_2*Related_Index

departing_males =
if(Potential_Helpers_per_Cluster_w_BP>unoccupied_usable_cavs\cluster)then(((Potential_Helpers_p er_Cluster_w_BP-unoccupied_usable_cavs\cluster)*(Foraging_Area_Factor_2)*(Clusters_w_Breedin g_Pair)))else(0)

excess_BP_due_to_lack_of_clusters =
if(Potential_Breeding_Pairs>Clusters_w\o_Breeding_Pair)then(Potential_Breeding_Pairs-Clusters_w\o _Breeding_Pair)else(0)

excess_females_due_to_lack_of_males =
if(Females_of_Breeding_Age>Males_of_Breeding_Age)then(Females_of_Breeding_Age-Males_of_Br eeding_Age)else(0)

Females_of_Breeding_Age =
F_Five_Year_Old+F_Four_Year_Old+F_One_Year_Old+F_Six_Year_Old+F_Three_Year_Old+F_Two _Year_Old

FF_Mortality_Rate = .66

Five_Mortality_Rate = .17

Four_Mortality_Rate = .3

F_Mortality_Rate = .6

F_Pop_Change = FF_to_One-Total_F_Mortality

Helpers_per_Cluster_w\BP = Helpers_Stock/Clusters_w_Breeding_Pair

Life_Span_Factor = 6/6

LLP_forag_area = LLP_forag_area_per_acre*Area

Males_of_Breeding_Age =
Five_Year_Old+Four_Year_Old+One_Year_Old+Six_Year_Old+Three_Year_Old+Two_Year_Old

MF_Mortality_Rate = .56

M_Five_Mortality_Rate = .21

M_Four_Mortality_Rate = .18

M_Mortality_Rate = .6

- M_One_Mortality_Rate = .26
- M_Pop_Change = MF_to_One-Total_M_Mortality
- M_Three_Mortality_Rate = .21
- M_Two_Mortality_Rate = .21
- One_Mortality_Rate = .33
- Potential_Breeding_Pairs = IF(Males_of_Breeding_Age>Females_of_Breeding_Age)THEN(Females_of_Breeding_Age-Clusters_w_Breeding_Pair)ELSE(Males_of_Breeding_Age-Clusters_w_Breeding_Pair)
- Potential_Helpers_per_Cluster_w_BP = Potential_Helpers_Stock/(Clusters_w_Breeding_Pair)
- RCW_Pop_Change = (F_Pop_Change+M_Pop_Change)-(Total_Departing_Females+Total_Departing_Males)
- req_basal_area_per_bird = 60
- Three_Mortality_Rate = .28
- Total_Departing_Females = Departing_F_Fives+Departing_F_Fours+Departing_F_Sixes+Departing_F_Threes+Departing_F_Twos +Departing__F_Ones
- Total_Departing_Males = Departing_M_Fives+Departing_M_Fours+Departing_M_Ones+Departing_M_Sixes+Departing_M_Threes+Departing_M_Twos
- Total_Females = Female_Fledgling+Females_of_Breeding_Age
- Total_F_Mortality = Five_Mortality+Four_Mortality+F_Mortality+One_Mortality+Three_Mortality+Two_Mortality
- Total_Males = Males_of_Breeding_Age+Male_Fledgling
- Total_M_Mortality = M_Five_Mortality+M_Four_Mortality+M_Mortality+M_One_Mortality+M_Three_Mortality+M_Two_Mortality
- Total_RCW_Population = Total_Males+Total_Females
- Two_Mortality_Rate = .27
- unoccupied_usable_cavs\cluster = Acpt_Avail_Cav/Total_Clusters
- Foraging_Area_Factor = GRAPH(basal_area_per_bird-req_basal_area_per_bird)
(-10.0, 0.08), (-9.00, 0.08), (-8.00, 0.095), (-7.00, 0.1), (-6.00, 0.115), (-5.00, 0.145), (-4.00, 0.205), (-3.00, 0.27), (-2.00, 0.38), (-1.00, 0.7), (0.00, 1.00)
- Foraging_Area_Factor_2 = GRAPH(basal_area_per_bird-req_basal_area_per_bird)
(-10.0, 1.75), (-9.00, 1.73), (-8.00, 1.70), (-7.00, 1.63), (-6.00, 1.52), (-5.00, 1.14), (-4.00, 1.06), (-3.00, 1.03), (-2.00, 1.02), (-1.00, 1.00), (0.00, 1.00)
- F_Birth_Rate_per_Breeding_Pair = GRAPH(Foraging_Area_Factor)
(0.00, 0.0125), (0.1, 0.725), (0.2, 0.901), (0.3, 1.02), (0.4, 1.10), (0.5, 1.16), (0.6, 1.19), (0.7, 1.21), (0.8, 1.22), (0.9, 1.23), (1, 1.25)
- Helper_per_Cluster_Factor = GRAPH(Helpers_per_Cluster_w\BP)
(0.00, 1.00), (0.4, 0.999), (0.8, 0.995), (1.20, 0.99), (1.60, 0.953), (2.00, 0.82), (2.40, 0.785), (2.80, 0.77), (3.20, 0.764), (3.60, 0.755), (4.00, 0.751)
- M_Birth_Rate_per_Breeding_Pair = GRAPH(Foraging_Area_Factor)
(0.00, 0.0125), (0.1, 0.625), (0.2, 0.973), (0.3, 1.11), (0.4, 1.13), (0.5, 1.16), (0.6, 1.19), (0.7, 1.20), (0.8, 1.21), (0.9, 1.23), (1, 1.25)

Relatedness = GRAPH(Total_RCW_Population)
(0.00, 1.00), (2.50, 0.5), (5.00, 0.305), (7.50, 0.15), (10.0, 0.095), (12.5, 0.055), (15.0, 0.025), (17.5, 0.02), (20.0, 0.015), (22.5, 0.01), (25.0, 0.005)

Related_Index = GRAPH(Relatedness)
(0.00, 1.00), (0.1, 1.27), (0.2, 1.41), (0.3, 1.46), (0.4, 1.48), (0.5, 1.50), (0.6, 1.50), (0.7, 1.50), (0.8, 1.50), (0.9, 1.50), (1, 1.50)

Tree

LLP_1_to_30(t) = LLP_1_to_30(t - dt) + (LLP_1to30_germ - LLP_1to30_mort - LLP_1to30_mech_removal - maturation_rate1) * dt
INIT LLP_1_to_30 = 2400000

DOCUMENT: This initial stock of trees has a diameter at breast height (dbh) that varies from 0 to approximately ?? cm for trees age 0 to 25 years of age [Platt et al, 500].

Units: # LLP 1to25

INFLOWS:

LLP_1to30_germ = Mature_LLP_density*LLP_germ*Area
DOCUMENT: Units: # LLP/year

OUTFLOWS:

LLP_1to30_mort = (LLP_1to30_Ips_beetle_infest+LLP_1to30_SPB_infest+Ntrl_Mort_1to30+LLP_1to30_%_dth_per_burn)*LLP_1_to_30
DOCUMENT: Units: # LLP 1to25/year

LLP_1to30_mech_removal = Area*excess_LLP_1to30/LLP_time_bet_thinning
DOCUMENT: LLP removed depends upon the tree removal rate per acre and the acreage.

Units: LLP 1to25 removed/year

maturation_rate1 = LLP_1_to_30/30
DOCUMENT: Untis: # LLP 1to25/year

LLP_30_to_60(t) = LLP_30_to_60(t - dt) + (maturation_rate1 - LLP_30to60_mort_rate - maturation_rate2 - LLP_30to60_mech_removal_rate) * dt
INIT LLP_30_to_60 = 320000

DOCUMENT: This second stock of trees has a diameter at breast height (dbh) that varies from ?? to approximately ?? cm for trees age 25 to 60 years of age [Platt et al, 500]. These trees are prime foraging habitat for RCWs.

Units: # LLP 25to60

INFLOWS:

maturation_rate1 = LLP_1_to_30/30
DOCUMENT: Untis: # LLP 1to25/year

OUTFLOWS:

LLP_30to60_mort_rate = (LLP_30to60_Ips_beetle_infest+LLP_30to60_SPB_infest+(Nat_Mort_Multiplier*Ntrl_Mort_30to60)+LLP_30to60_%_dth_per_burn)*LLP_30_to_60
DOCUMENT: The mortality rate for LLP 20 to 30 cm dbh is as follows [Platt et al, 500]:

Size (dbh)	Mortality
20-30 cm	.25%

Units: # LLP 25to60/year

maturation_rate2 = LLP_30_to_60/30
DOCUMENT: Units: # LLP 25to60/year

LLP_30to60_mech_removal_rate = Area*excess_LLP_30to60/LLP_time_bet_thinning
DOCUMENT: Units: LLP 25to60 removed/year

☐ LLP_60to95(t) = LLP_60to95(t - dt) + (maturation_rate2 - LLP_60to95_mort - maturation_rate_3 - LLP_60to95_mech_removal_rate) * dt
INIT LLP_60to95 = 20000

DOCUMENT: This stock of trees has a diameter at breast height (dbh) that exceeds ?? for trees age 60 years of age and older [Platt et al, 500]. These trees provide prime foraging habitat as well as potentential artificial cavity sites for the RCW.

Units: # LLP 60to95

INFLOWS:

maturation_rate2 = LLP_30_to_60/30
DOCUMENT: Units: # LLP 25to60/year

OUTFLOWS:

LLP_60to95_mort = (LLP_60to95_Ips_beetle_infest+LLP_60to95_SPB_infest+(Ntrl_Mort_60to95*Nat_Mort_Multiplier)+LLP_60to95_%_dth_per_burn)*LLP_60to95
DOCUMENT: Units: # LLP 60to95/year

maturation_rate_3 = LLP_60to95/35
DOCUMENT: Units: # LLP 60to95/year

LLP_60to95_mech_removal_rate = Area*excess_LLP_60to95/LLP_time_bet_thinning
DOCUMENT: Units: # LLP 60to95 removed/year

☐ LLP_95_plus(t) = LLP_95_plus(t - dt) + (maturation_rate_3 - LLP_95plus_mort - LLP_95plus_mech_removal_rate) * dt
INIT LLP_95_plus = 300

DOCUMENT: This stock of trees has a diameter at breast height (dbh) that exceeds ?? for trees age 95 years of age and older [Platt et al, 500]. This stock is in basal area per acre of tree age 60 plus. These trees provide prime foraging habitat, potentential artificial cavity sites for the RCW, and pioneering sites for the RCW.

Units: # LLP 95plus

INFLOWS:

maturation_rate_3 = LLP_60to95/35
DOCUMENT: Units: # LLP 60to95/year

OUTFLOWS:

LLP_95plus_mort =
(LLP_95plus_Ips_beetle_infest+LLP_95plus_SPB_infest+(Ntrl_Mort_95plus*Nat_Mort_Multiplier)+LLP_95plus_%_dth_per_burn)*LLP_95_plus
DOCUMENT: Units: # LLP 95plus/year

LLP_95plus_mech_removal_rate = Area*excess_LLP_95plus/LLP_time_bet_thinning
DOCUMENT: Units: # LLP 95plus removed/year

☐ Turkey_Oak(t) = Turkey_Oak(t - dt) + (TO_germ - TO_mort_rate - TO_mech_removed) * dt
INIT Turkey_Oak = 1600000

DOCUMENT: This initial figure is from the sandhill reserve in Georgia, for total number of TOs.

Units: # of TOs

INFLOWS:

TO_germ = (TO_Dth_Per_Brn*.67/burn_time)+(Turkey_Oak*TO_germ_rate)
DOCUMENT: THis assumes that 67% of those TO's killed will resprout. (Rebertus and others: 62-64)
Additionally, natural germination rate which varies with shading, going from 0 to 5% is also assumed.

Units: TO/year

OUTFLOWS:

TO_mort_rate = (TO_Dth_Per_Brn*Turkey_Oak/burn_time)+(TO_Ntrl_Mort*Turkey_Oak)
DOCUMENT: The total number of turkey oaks that are killed each year. This is the sum of those that are killed due to burning and those that die from natural mortality.

Units: burning*TO dth per burn = burns per year*TO death per burn = TO deaths per year
TO natrl mort rate*TO = (TO deaths per TO*yr)*TO = TO deaths per year

TO_mech_removed = Area*excess_TO/TO_time_bet_thinning
DOCUMENT: The TO removed will be dependent upon the removal rate and the Poinsett area.

Units: TO removed/year

Area = 8000
DOCUMENT: This is the Poinsett LLP forest area.

Unit: acres

burn_time = 4
DOCUMENT: Units: years

burn_weight_1to30 = .5
DOCUMENT: Units: NA

burn_weight_30to60 = .3
DOCUMENT: Units: NA

burn_weight_60plus = .2
DOCUMENT: Units: NA

excess_LLP_1to30 =
IF(LLP_1to30_stem_dens-LLP_1to30_ideal_stem_dens<0)THEN(0)ELSE(LLP_1to30_stem_dens-LLP_1to30_ideal_stem_dens)
DOCUMENT: Units: # LLP 1to25/acre

excess_LLP_30to60 =
IF(LLP_30to60_stem_dens-LLP_30to60_ideal_stem_dens<0)THEN(0)ELSE(LLP_30to60_stem_dens-LLP_30to60_ideal_stem_dens)
DOCUMENT: Units: LLP 25to60/acre

excess_LLP_60to95 =
IF(LLP_60to95_stem_dens-LLP_60to95_ideal_stem_dens<0)THEN(0)ELSE(LLP_60to95_stem_dens-LLP_60to95_ideal_stem_dens)
DOCUMENT: Units: # LLP 60to95/acre

○ excess_LLP_95plus =
IF(LLP_95plus_stem_dens-LLP_95plus_ideal_stem_dens<0)THEN(0)ELSE(LLP_95plus_stem_dens-LLP_95plus_ideal_stem_dens)
DOCUMENT: Units: # LLP 95plus/acre

○ excess_TO =
IF(TO_stem_density-TO_ideal_stem_density<0)THEN(0)ELSE(TO_stem_density-TO_ideal_stem_density)
DOCUMENT: Units: TO/acre

○ fire_intensity =
IF(fire_management=1)THEN(MIN(.75,(.5*fuel)+(.5*Stem_Density_Fire_Fctr)))ELSE((.5*fuel)+(.5*Stem_Density_Fire_Fctr))
DOCUMENT: Units: Scale from 0 to 1

○ fire_management = 1
DOCUMENT: Units: On - 1, Off - 0

○ fuel = (TO_fuel*TO_weight)+(LLP_fuel*LLP_weight*time_bet_burns)
DOCUMENT: Units: #

○ LLP_1to30_basal_area = LLP_1_to_30*PI*(LLP_1to30_dbh/24)^2
DOCUMENT: Units: LLP 1to25 square feet

○ LLP_1to30_dbh = 4
DOCUMENT: Units: inch

○ LLP_1to30_ideal_stem_dens = 150
DOCUMENT: Units: # LLP 1to25/acre

○ LLP_1to30_stem_dens = LLP_1_to_30/Area
DOCUMENT: This density factor is necessary to determine how much thinning will be required of LLP.

Units: # LLP 1to25/acre

○ LLP_30to60_basal_area = LLP_30_to_60*PI*(LLP_30to60_dbh/24)^2
DOCUMENT: Units: LLP 25to60 square feet

○ LLP_30to60_dbh = 12
DOCUMENT: Units: inch

○ LLP_30to60_ideal_stem_dens = 20
DOCUMENT: Units: LLP 25to60/acre

○ LLP_30to60_stem_dens = LLP_30_to_60/Area
DOCUMENT: Units: LLP 25to60/acre

○ LLP_60to95_basal_area = LLP_60to95*PI*(LLP_60to95_dbh/24)^2
DOCUMENT: Units: LLP 60to95 square feet

○ LLP_60to95_dbh = 18
DOCUMENT: Units: inch

○ LLP_60to95_ideal_stem_dens = 15
DOCUMENT: Units: # LLP 60to95/acre

○ LLP_60to95_stem_dens = LLP_60to95/Area
DOCUMENT: Units: # LLP 60to95/acre

○ LLP_95plus_basal_area = LLP_95_plus*PI*(LLP_95plus_dbh/24)^2
DOCUMENT: Units: LLP 95plus square feet

○ LLP_95plus_dbh = 22
DOCUMENT: Units: inch

○ LLP_95plus_ideal_stem_dens = 10
DOCUMENT: Units: # LLP 95plus/acre

○ LLP_95plus_stem_dens = LLP_95_plus/Area
DOCUMENT: Units: # LLP 95plus/acre

○ LLP_basal_area =
LLP_1to30_basal_area+LLP_30to60_basal_area+LLP_60to95_basal_area+LLP_95plus_basal_area
DOCUMENT: By law the cluster pine basal area is 14-16 meters squared per hectare
[Conner&Rudolph, 82].

Units: Square feet of LLP

○ LLP_burn_weight = .1
DOCUMENT: Units: NA

○ LLP_density = (LLP_1_to_30+LLP_30_to_60+LLP_60to95+LLP_95_plus)/Area
DOCUMENT: Units: Total LLP/acre

○ LLP_forag_area_per_acre =
(LLP_30to60_basal_area+LLP_60to95_basal_area+LLP_95plus_basal_area)/Area

- LLP_mech_rem_weight = .3
  DOCUMENT: Units: NA

- LLP_time_bet_thinning = 8
  DOCUMENT: Units: years

- LLP_weight = .66
  DOCUMENT: Units: NA

- LLP__basal_area_density_weight = .6
  DOCUMENT: Units: NA

- Mature_LLP_density = (LLP_30_to_60+LLP_60to95+LLP_95_plus)/Area
  DOCUMENT: Units: # LLP 25plus/acre

- Nat_Mort_Multiplier = 1
- Shading = LLP_Shading+TO_Shading
  DOCUMENT: Units: %

- Stem_Density_Fire_Fctr =
  (burn_weight_1to30*LLP_1to30_SD_Fctr)+(burn_weight_30to60*LLP_30t60_SD_Fctr)+(burn_weight_60plus*LLP_60plus_SD_Fctr)
  DOCUMENT: Units: Total trees/acre

- total_basal_area =
  LLP_1to30_basal_area+LLP_30to60_basal_area+LLP_60to95_basal_area+LLP_95plus_basal_area+TO_basal_area
  DOCUMENT: Units: Square feet LLP & TO

- Total_LLP_1to30_health =
  (LLP_burn_weight*LLP_1to30__burn_health)+(LLP_mech_rem_weight*LLP_1to30_mech_rem_health)+(LLP__basal_area_density_weight*LLP_1to30__ba_health)
  DOCUMENT: Units: %

- Total_LLP_30to60_health =
  (LLP_burn_weight*LLP_30to60__burn_health)+(LLP_mech_rem_weight*LLP_30to60__mech_rem_health)+(LLP__basal_area_density_weight*LLP_30to60__ba_health)
  DOCUMENT: Units: %

- Total_LLP_60to95_health =
  (LLP_burn_weight*LLP_60to95__burn_health)+(LLP_mech_rem_weight*LLP_60to95__mech_rem_health)+(LLP__basal_area_density_weight*LLP_60to95__ba_health)
  DOCUMENT: Units: %

○ Total_LLP_95plus_health = (LLP_burn_weight*LLP_95plus__burn_health)+(LLP_mech_rem_weight*LLP_95plus__mech_rem_health)+(LLP__basal_area_density_weight*LLP_95plus__ba_health)
DOCUMENT: Units: %

○ TO_basal_area = Turkey_Oak*PI*(TO_dbh/24)^2
DOCUMENT: Units: Square feet of TO

○ TO_dbh = 4
DOCUMENT: Units: inch

○ TO_ideal_stem_density = 50
DOCUMENT: Units: TO/acre

○ TO_stem_density = Turkey_Oak/Area
DOCUMENT: This density factor is necessary to determine what the mechanical removal rates will be.

Units: TO/acre

○ TO_time_bet_thinning = 4
DOCUMENT: Units: years

○ TO_weight = .33
DOCUMENT: Units: NA

⊘ LLP_1to30_%_dth_per_burn = GRAPH(fire_intensity)
(0.00, 0.00), (0.1, 0.03), (0.2, 0.055), (0.3, 0.085), (0.4, 0.12), (0.5, 0.145), (0.6, 0.185), (0.7, 0.23), (0.8, 0.355), (0.9, 0.615), (1, 0.995)
DOCUMENT: Units: % LLP 1to25 burn/year

⊘ LLP_1to30_Ips_beetle_infest = GRAPH(Total_LLP_1to30_health)
(0.2, 0.0199), (0.28, 0.0146), (0.36, 0.0112), (0.44, 0.0083), (0.52, 0.00551), (0.6, 0.0038), (0.68, 0.00308), (0.76, 0.00263), (0.84, 0.00227), (0.92, 0.00218), (1, 0.002)
DOCUMENT: Units: % LLP 1to25/year

⊘ LLP_1to30_mech_rem_health = GRAPH(LLP_1to30_mech_removal/Area)
(0.00, 0.005), (0.5, 0.035), (1.00, 0.065), (1.50, 0.15), (2.00, 0.26), (2.50, 0.41), (3.00, 0.61), (3.50, 0.8), (4.00, 0.93), (4.50, 0.975), (5.00, 1.00)
DOCUMENT: Units: % LLP 1to25

⊘ LLP_1to30_SD_Fctr = GRAPH(LLP_1to30_stem_dens)
(0.00, 0.00), (30.0, 0.02), (60.0, 0.045), (90.0, 0.105), (120, 0.255), (150, 0.41), (180, 0.585), (210, 0.79), (240, 0.915), (270, 0.975), (300, 1.00)

LLP_1to30_SPB_infest = GRAPH(Total_LLP_1to30_health)
(0.00, 0.905), (0.1, 0.815), (0.2, 0.67), (0.3, 0.425), (0.4, 0.00), (0.5, 0.00), (0.6, 0.00), (0.7, 0.00), (0.8, 0.00), (0.9, 0.00), (1, 0.00)
DOCUMENT: Units: % LLP 1to25/year

LLP_1to30__ba_health = GRAPH(total_basal_area/Area)
(0.00, 1.00), (18.0, 1.00), (36.0, 1.00), (54.0, 0.975), (72.0, 0.93), (90.0, 0.835), (108, 0.735), (126, 0.49), (144, 0.21), (162, 0.055), (180, 0.00)
DOCUMENT: Units: % LLP 1to25

LLP_1to30__burn_health = GRAPH(burn_time)
(0.00, 0.00), (1.00, 0.165), (2.00, 0.325), (3.00, 0.475), (4.00, 0.595), (5.00, 0.71), (6.00, 0.825), (7.00, 0.895), (8.00, 0.95), (9.00, 0.98), (10.0, 1.00)
DOCUMENT: Units: % LLP 1to25

LLP_30t60_SD_Fctr = GRAPH(LLP_30to60_stem_dens)
(0.00, 0.005), (8.00, 0.035), (16.0, 0.065), (24.0, 0.16), (32.0, 0.295), (40.0, 0.47), (48.0, 0.64), (56.0, 0.81), (64.0, 0.915), (72.0, 0.97), (80.0, 1.00)

LLP_30to60_%_dth_per_burn = GRAPH(fire_intensity)
(0.00, 0.00), (0.1, 0.02), (0.2, 0.035), (0.3, 0.06), (0.4, 0.075), (0.5, 0.09), (0.6, 0.12), (0.7, 0.15), (0.8, 0.225), (0.9, 0.455), (1, 0.805)
DOCUMENT: Units: % LLP 25to60 burn/year

LLP_30to60_Ips_beetle_infest = GRAPH(Total_LLP_30to60_health)
(0.2, 0.0198), (0.28, 0.0146), (0.36, 0.011), (0.44, 0.00839), (0.52, 0.0056), (0.6, 0.00389), (0.68, 0.00308), (0.76, 0.00272), (0.84, 0.00245), (0.92, 0.00227), (1, 0.002)
DOCUMENT: Units: % LLP 25to60/year

LLP_30to60_SPB_infest = GRAPH(Total_LLP_30to60_health)
(0.00, 0.905), (0.1, 0.815), (0.2, 0.67), (0.3, 0.425), (0.4, 0.00), (0.5, 0.00), (0.6, 0.00), (0.7, 0.00), (0.8, 0.00), (0.9, 0.00), (1, 0.00)
DOCUMENT: Units: % LLP 25to60/year

LLP_30to60__ba_health = GRAPH(total_basal_area/Area)
(0.00, 1.00), (18.0, 1.00), (36.0, 1.00), (54.0, 0.97), (72.0, 0.93), (90.0, 0.85), (108, 0.65), (126, 0.24), (144, 0.1), (162, 0.02), (180, 0.00)
DOCUMENT: Units: % LLP 25to60

LLP_30to60__burn_health = GRAPH(burn_time)
(0.00, 0.00), (1.00, 0.215), (2.00, 0.35), (3.00, 0.505), (4.00, 0.615), (5.00, 0.72), (6.00, 0.805), (7.00, 0.88), (8.00, 0.94), (9.00, 0.975), (10.0, 1.00)
DOCUMENT: Units: % LLP 25to60

LLP_30to60__mech_rem_health = GRAPH(LLP_30to60_mech_removal_rate/Area)
(0.00, 0.015), (0.1, 0.2), (0.2, 0.32), (0.3, 0.445), (0.4, 0.56), (0.5, 0.68), (0.6, 0.795), (0.7, 0.9), (0.8, 0.955), (0.9, 0.99), (1, 1.00)
DOCUMENT: Units: % LLP 25to60

LLP_60plus_SD_Fctr = GRAPH(LLP_60to95_stem_dens+LLP_95plus_stem_dens)
(0.00, 0.00), (5.00, 0.015), (10.0, 0.045), (15.0, 0.115), (20.0, 0.295), (25.0, 0.455), (30.0, 0.63), (35.0, 0.82), (40.0, 0.935), (45.0, 0.98), (50.0, 1.00)

LLP_60to95_%_dth_per_burn = GRAPH(fire_intensity)
(0.00, 0.00), (0.1, 0.0125), (0.2, 0.02), (0.3, 0.0275), (0.4, 0.0375), (0.5, 0.0475), (0.6, 0.055), (0.7, 0.075), (0.8, 0.12), (0.9, 0.29), (1, 0.5)
DOCUMENT: Units: % LLP 60to95 burn/year

LLP_60to95_Ips_beetle_infest = GRAPH(Total_LLP_60to95_health)
(0.00, 0.02), (0.1, 0.0146), (0.2, 0.0108), (0.3, 0.00776), (0.4, 0.0056), (0.5, 0.00371), (0.6, 0.00308), (0.7, 0.00272), (0.8, 0.00245), (0.9, 0.00236), (1, 0.00218)
DOCUMENT: Units: % LLP 60to95/year

LLP_60to95_SPB_infest = GRAPH(Total_LLP_60to95_health)
(0.00, 0.905), (0.1, 0.815), (0.2, 0.67), (0.3, 0.425), (0.4, 0.00), (0.5, 0.00), (0.6, 0.00), (0.7, 0.00), (0.8, 0.00), (0.9, 0.00), (1, 0.00)
DOCUMENT: Units: % LLP 60to95/year

LLP_60to95__ba_health = GRAPH(total_basal_area/Area)
(0.00, 1.00), (18.0, 1.00), (36.0, 0.975), (54.0, 0.945), (72.0, 0.9), (90.0, 0.795), (108, 0.565), (126, 0.24), (144, 0.115), (162, 0.045), (180, 0.00)
DOCUMENT: Units: % LLP 60to95

LLP_60to95__burn_health = GRAPH(burn_time)
(0.00, 0.01), (1.00, 0.195), (2.00, 0.345), (3.00, 0.505), (4.00, 0.61), (5.00, 0.725), (6.00, 0.81), (7.00, 0.895), (8.00, 0.945), (9.00, 0.975), (10.0, 1.00)
DOCUMENT: Units: % LLP 60to95

LLP_60to95__mech_rem_health = GRAPH(LLP_60to95_mech_removal_rate/Area)
(0.00, 0.01), (0.05, 0.165), (0.1, 0.295), (0.15, 0.45), (0.2, 0.59), (0.25, 0.725), (0.3, 0.815), (0.35, 0.89), (0.4, 0.94), (0.45, 0.97), (0.5, 1.00)
DOCUMENT: Units: % LLP 60to95

LLP_95plus_%_dth_per_burn = GRAPH(fire_intensity)
(0.00, 0.00), (0.1, 0.0125), (0.2, 0.0225), (0.3, 0.035), (0.4, 0.045), (0.5, 0.055), (0.6, 0.065), (0.7, 0.0775), (0.8, 0.128), (0.9, 0.215), (1, 0.299)
DOCUMENT: Units: % LLP 95plus burn/year

⊘ LLP_95plus_Ips_beetle_infest = GRAPH(Total_LLP_95plus_health)
(0.00, 0.0199), (0.1, 0.0146), (0.2, 0.011), (0.3, 0.00839), (0.4, 0.0056), (0.5, 0.00389), (0.6, 0.00317), (0.7, 0.00272), (0.8, 0.00245), (0.9, 0.00227), (1, 0.00209)
DOCUMENT: Units: % LLP 95plus/year

⊘ LLP_95plus_SPB_infest = GRAPH(Total_LLP_95plus_health)
(0.00, 0.905), (0.1, 0.815), (0.2, 0.67), (0.3, 0.425), (0.4, 0.00), (0.5, 0.00), (0.6, 0.00), (0.7, 0.00), (0.8, 0.00), (0.9, 0.00), (1, 0.00)
DOCUMENT: Units: % LLP 95plus/year

⊘ LLP_95plus__ba_health = GRAPH(total_basal_area/Area)
(0.00, 1.00), (18.0, 0.99), (36.0, 0.98), (54.0, 0.965), (72.0, 0.92), (90.0, 0.835), (108, 0.665), (126, 0.235), (144, 0.085), (162, 0.025), (180, 0.00)
DOCUMENT: Units: % LLP 95plus

⊘ LLP_95plus__burn_health = GRAPH(burn_time)
(0.00, 0.01), (1.00, 0.26), (2.00, 0.465), (3.00, 0.655), (4.00, 0.77), (5.00, 0.865), (6.00, 0.915), (7.00, 0.955), (8.00, 0.97), (9.00, 0.985), (10.0, 0.995)
DOCUMENT: Units: % LLP 95plus

⊘ LLP_95plus__mech_rem_health = GRAPH(LLP_95plus_mech_removal_rate/Area)
(0.00, 0.005), (0.1, 0.21), (0.2, 0.385), (0.3, 0.545), (0.4, 0.685), (0.5, 0.78), (0.6, 0.865), (0.7, 0.925), (0.8, 0.965), (0.9, 0.98), (1, 0.995)
DOCUMENT: Units: % LLP 95plus

⊘ LLP_fuel = GRAPH(LLP_basal_area/Area)
(0.00, 0.00), (15.0, 0.11), (30.0, 0.2), (45.0, 0.305), (60.0, 0.41), (75.0, 0.5), (90.0, 0.62), (105, 0.7), (120, 0.795), (135, 0.89), (150, 1.00)
DOCUMENT: Units:

⊘ LLP_germ = GRAPH(Shading)
(0.00, 0.597), (0.1, 0.591), (0.2, 0.585), (0.3, 0.567), (0.4, 0.537), (0.5, 0.501), (0.6, 0.42), (0.7, 0.303), (0.8, 0.063), (0.9, 0.009), (1, 0.00)
DOCUMENT: Units: % mature LLP

⊘ LLP_Shading = GRAPH(LLP_density)
(0.00, 0.00), (30.0, 0.077), (60.0, 0.14), (90.0, 0.189), (120, 0.222), (150, 0.246), (180, 0.266), (210, 0.279), (240, 0.288), (270, 0.294), (300, 0.3)
DOCUMENT: Units: %

Ntrl_Mort_1to30 = GRAPH(Total_LLP_1to30_health)
(0.2, 0.099), (0.28, 0.0969), (0.36, 0.0942), (0.44, 0.091), (0.52, 0.0861), (0.6, 0.0811), (0.68, 0.073), (0.76, 0.0636), (0.84, 0.0492), (0.92, 0.0307), (1, 0.01)
DOCUMENT: The mortality rate for LLP 0 to 20 cm dbh is as follows [Platt et al, 500]:

Size (dbh)	Mortality
<10 cm	4-5%
10-20 cm	.75%

Assuming an equivalent number of trees in each category, this gives an average intrinsic mortality in this class of approximately 2.9%

Based upon the fact that our tree health will vary with burning, our natural mortality will also vary with the health.

Units: % LLP 1to25/year

ml

Ntrl_Mort_30to60 = GRAPH(Total_LLP_30to60_health)
(0.00, 0.01), (0.1, 0.00991), (0.2, 0.00987), (0.3, 0.00978), (0.4, 0.00955), (0.5, 0.00928), (0.6, 0.00883), (0.7, 0.00825), (0.8, 0.00712), (0.9, 0.00496), (1, 0.001)
DOCUMENT: The mortality rate for LLP 20 to 30 cm dbh is as follows [Platt et al, 500]:

Size (dbh)	Mortality
20-30 cm	.25%

Based upon the fact that our tree health will vary with burning, our natural mortality will also vary with the health.

Units: % LLP 25to60/year

Ntrl_Mort_60to95 = GRAPH(Total_LLP_60to95_health)
(0.00, 0.00995), (0.1, 0.00987), (0.2, 0.00987), (0.3, 0.00982), (0.4, 0.00969), (0.5, 0.00942), (0.6, 0.00906), (0.7, 0.00856), (0.8, 0.00748), (0.9, 0.0055), (1, 0.001)
DOCUMENT: The mortality rate for LLP 30 to 70 plus cm dbh is as follows [Platt et al, 500]:

Size (dbh)	Mortality
30-40 cm	.5%
40-50 cm	.75%
50-60 cm	1%

Assuming an equal distribution, this gives an average intrinsic mortality in this class of approximately .75%

Based upon the fact that our tree health will vary with burning, our natural mortality will also vary with the health.

Units: % LLP 60to95/year

Ntrl_Mort_95plus = GRAPH(Total_LLP_95plus_health)
(0.00, 0.0496), (0.1, 0.0496), (0.2, 0.0491), (0.3, 0.0487), (0.4, 0.048), (0.5, 0.0471), (0.6, 0.0462), (0.7, 0.0437), (0.8, 0.0376), (0.9, 0.0257), (1, 0.00545)
DOCUMENT: The mortality rate for LLP 30 to 70 plus cm dbh is as follows [Platt et al, 500]:

Size (dbh)	Mortality
30-40 cm	.5%
40-50 cm	.75%
50-60 cm	1%
60-70 cm	1.67%
70 plus cm	3%

Assuming an equal distribution, this gives an average intrinsic mortality in this class of approximately 1.38%

Based upon the fact that our tree health will vary with burning, our natural mortality will also vary with the health.

Units: % LLP 95plus/year

time_bet_burns = GRAPH(burn_time)
(0.00, 0.005), (1.00, 0.19), (2.00, 0.37), (3.00, 0.535), (4.00, 0.69), (5.00, 0.82), (6.00, 0.925), (7.00, 0.96), (8.00, 0.975), (9.00, 0.99), (10.0, 1.00)
DOCUMENT: Units: years

TO_Dth_Per_Brn = GRAPH(fire_intensity)
(0.00, 0.00), (0.1, 0.03), (0.2, 0.065), (0.3, 0.11), (0.4, 0.17), (0.5, 0.255), (0.6, 0.35), (0.7, 0.475), (0.8, 0.61), (0.9, 0.745), (1, 0.9)
DOCUMENT: This is the rate at which turkey oaks will be killed by burns. It is dependent upon the density of the TO's, the greater the density, the more deaths there will be due to burns.

Units: TO killed/burn

TO_fuel = GRAPH(TO_basal_area/Area)
(0.00, 0.00), (1.00, 0.105), (2.00, 0.205), (3.00, 0.315), (4.00, 0.415), (5.00, 0.5), (6.00, 0.595), (7.00, 0.68), (8.00, 0.8), (9.00, 0.895), (10.0, 0.985)
DOCUMENT: Units: #

TO_germ_rate = GRAPH(Shading)
(0.00, 0.15), (0.1, 0.149), (0.2, 0.148), (0.3, 0.144), (0.4, 0.137), (0.5, 0.121), (0.6, 0.0832), (0.7, 0.0488), (0.8, 0.027), (0.9, 0.015), (1, 0.0075)
DOCUMENT: The TO natural germination rate is based on the shading of the LLP and TO forest. The assumption is that as the shading increases to 1 the TO germination rate goes to zero. The max TO germination rate is estimated as .05 when the shading factor is minimal.

Units: % TO/year

TO_Ntrl_Mort = GRAPH(total_basal_area/Area)
(0.00, 0.00), (15.0, 0.00075), (30.0, 0.002), (45.0, 0.005), (60.0, 0.01), (75.0, 0.0188), (90.0, 0.031), (105, 0.0425), (120, 0.0473), (135, 0.0493), (150, 0.0498)
DOCUMENT: Assuming that the maximum life span of a turkey oak is 40 year, when the density is maximum at 1100 the mortality is maximized at .1, and when the density is at a minimum of 0 the mortality is at 0.

Units: TO deaths/year

TO_Shading = GRAPH(TO_stem_density)
(0.00, 0.00), (100, 0.168), (200, 0.298), (300, 0.385), (400, 0.469), (500, 0.529), (600, 0.591), (700, 0.634), (800, 0.662), (900, 0.686), (1000, 0.7)
DOCUMENT: Units: %